

Cosmology and the origin of structure

<http://home.fnal.gov/~rocky/>

Rocky I: The universe observed

Rocky II: The growth of cosmological structures

Rocky III: Inflation and the origin of perturbations-1

Rocky IV: Inflation and the origin of perturbations-2

Rocky V: Dark matter

Xth Brazilian School of Cosmology and Gravitation

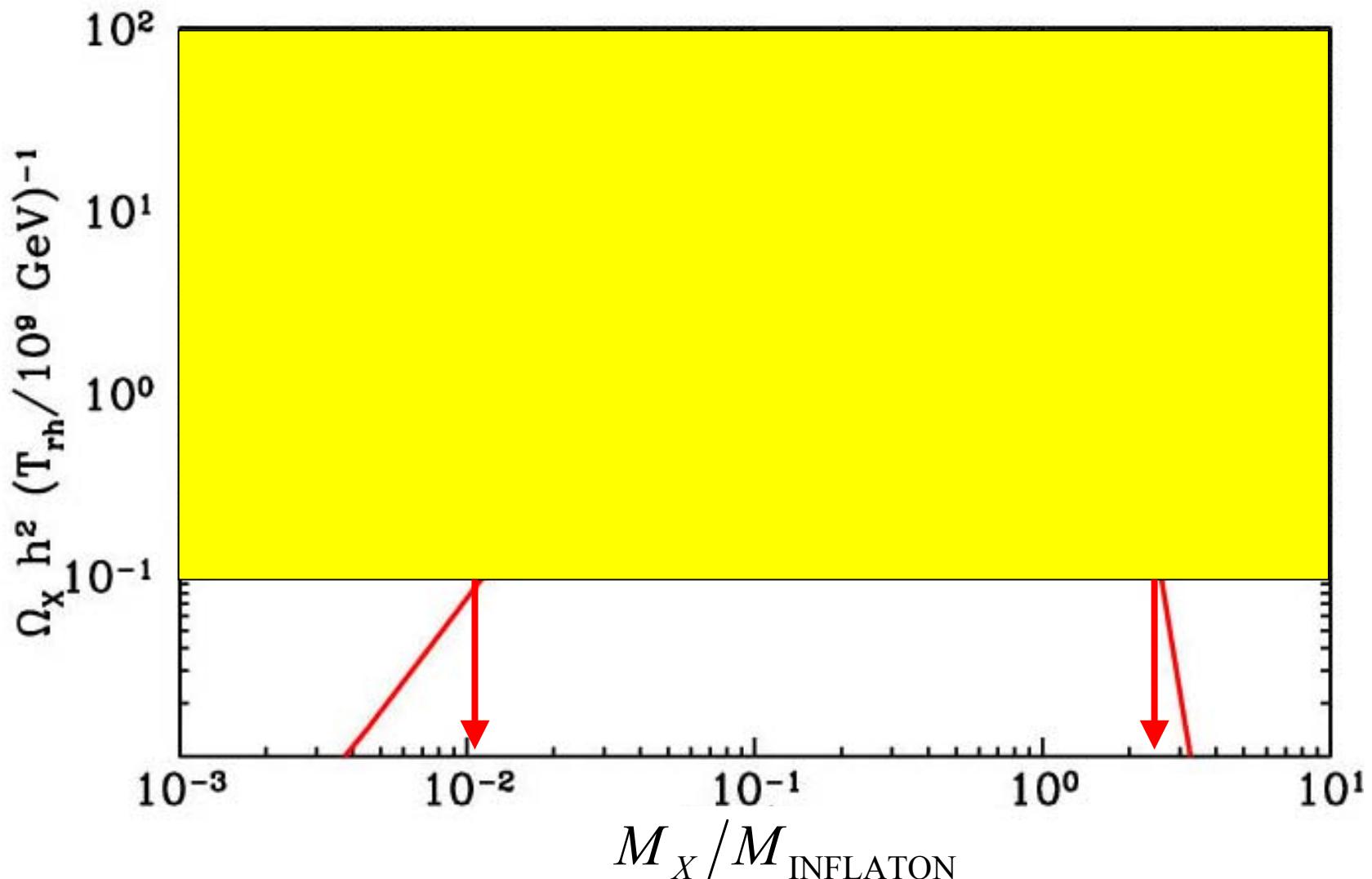
August 2002, Mangaratiba

Rocky Kolb

Fermilab, University of Chicago, & CERN

Particle production

Chung, Kolb, Riotto (also Kuzmin & Tkachev)



$\Omega_X \approx 1$ for $M_X/M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{ GeV}$

Superheavy particles

- Inflaton mass (in principle measurable from gravitational wave background, guess 10^{12} GeV) may signal a new mass scale in nature.
- Other particles may exist with mass comparable to the inflaton mass.
- Conserved quantum numbers may render the particle stable.

Long-lived superheavy particles!

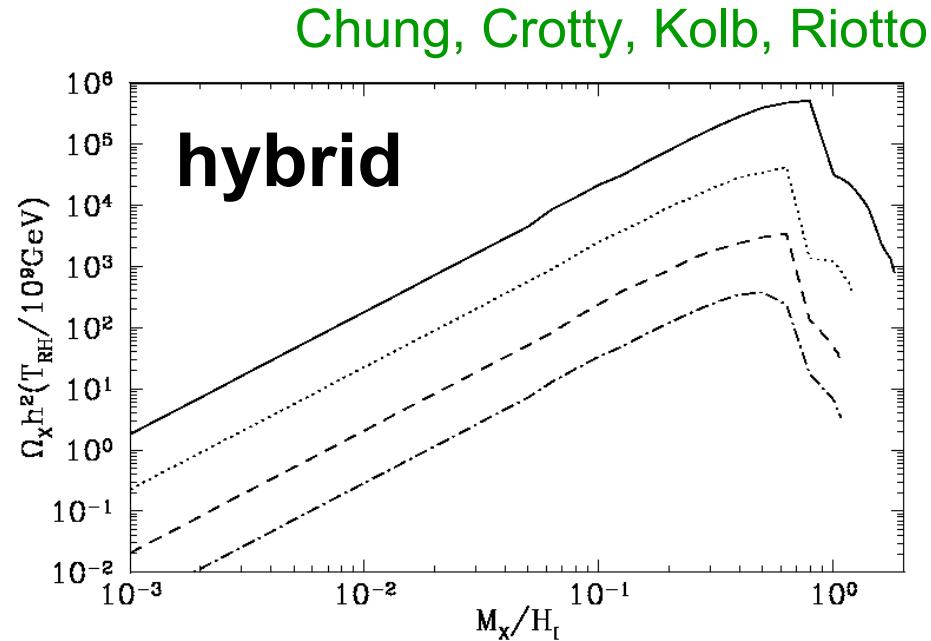
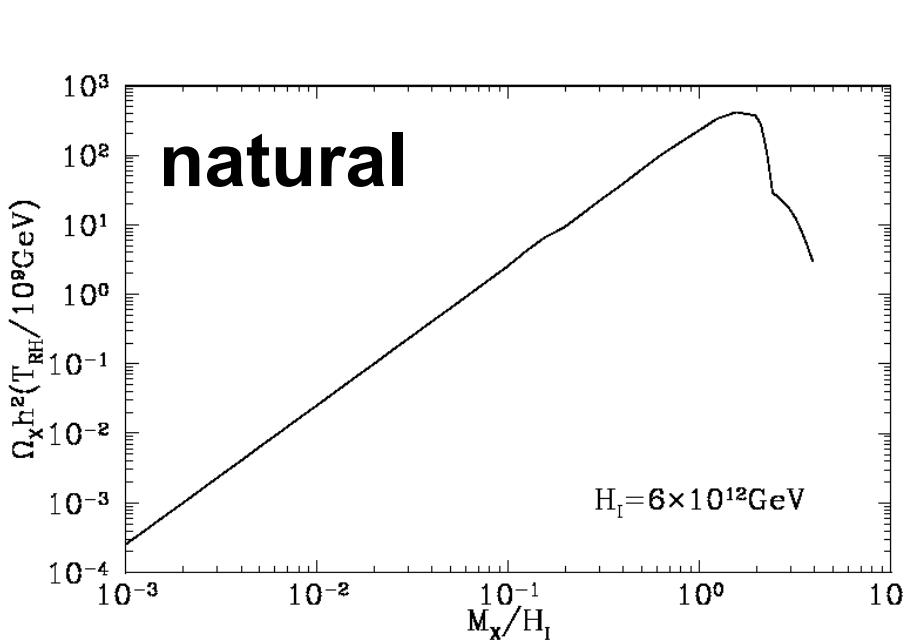
- In superstring models:
Ellis, Gelmini, Lopez, & Nanopoulos
- With discrete gauge symmetries:
Hamaguchi, Nomura, & Yanagida
- In dynamical SUSY breaking models:
Hamaguchi, Izawa, Nomura, & Yanagida
- Brane-world mechanisms:
Crooks, Dunn, & Frampton
- With conserved quantum numbers (possibly discrete):

Model exploration

Gravitational Production:

- Fermions Kuzmin & Tkachev
- Non-conformal couplings Kuzmin & Tkachev
- Small-field models Crotty, Chung, Kolb, Riotto
- Hybrid models Crotty, Chung, Kolb, Riotto

Model exploration



$$M_X \leq H_I \rightarrow \Omega_X h^2 \approx \left(\frac{M_X}{10^{11} \text{ GeV}} \right)^2 \left(\frac{T_{RH}}{10^9 \text{ GeV}} \right)$$

$$M_X \geq H_I \rightarrow \Omega_X h^2 \propto \exp(-M_X/H_I)$$

Isocurvature modes

Mode equation (τ =conforml time)

$$h_k''(\tau) + \left[k^2 + M_X^2 a^2 + (6\xi - 1) a''/a \right] h_k(\tau) = 0$$

$$h_k''(\tau) + \left[k^2 + M_X^2 a^2 - a''/a \right] h_k(\tau) = 0 \quad (\xi = 0)$$

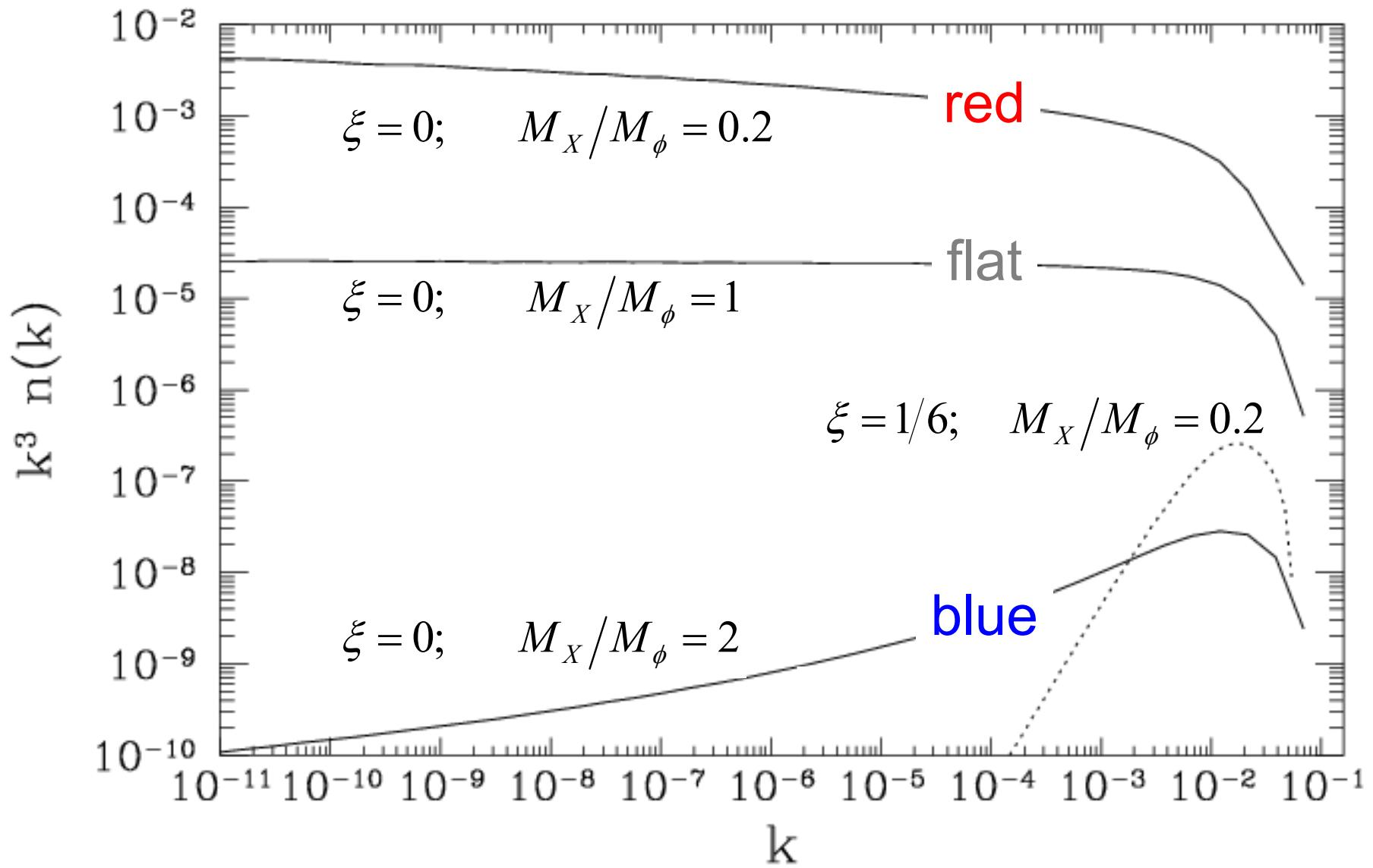


notice sign!

Isocurvature modes

Kuzmin & Tkachev

Chung, Kolb, Riotto, Senatore



Wimpzilla characteristics:

- supermassive: $10^9 - 10^{19}$ GeV ($\sim 10^{12}$ GeV ?)
- abundance may depend only on mass
- abundance may be independent of interactions
 - sterile?
 - electrically charged?
 - strong interactions?
 - weak interactions?
- unstable (lifetime > age of the universe)?

WIMPZILLA footprints:



Isocurvature modes:

CMB, Large-scale structure

Decay:

Ultra High Energy Cosmic Rays

Annihilate:

Galactic Center, Sun

Direct Detection:

Bulk, Underground Searches

Gravitino production

Giudice, Riotto, Tkachev

Linde, Kallosh, Kofman, Van Proeyen

Nilles, Peloso, Sorbo

Nilles, Olive, Peloso

.....

(perhaps it is a bug after all...)

Brane cosmology

- Old idea of extra dimensions and unification

Kaluza (1919) Klein (1926)

- Compact extra dimension
 - 5-D gravity \longrightarrow 4-D gravity + electrodynamics
 - Kaluza-Klein expansion

$$\phi(x, y) = \sum_{p=-\infty}^{\infty} e^{ipy/R} \phi_p(x)$$

- Massless scalar in 5 spacetime dimensions

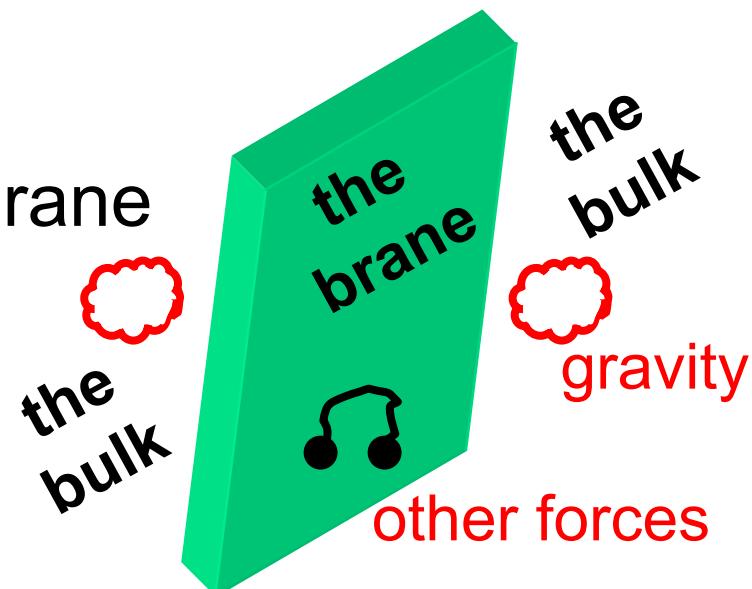
$$\square^{(5)} \phi = 0 \quad \rightarrow \quad \square^{(4)} \phi_p + \frac{p^2}{R^2} \phi_p = 0$$

- Infinite tower of Kaluza-Klein modes

$$m_p^2 = p^2 / R^2$$

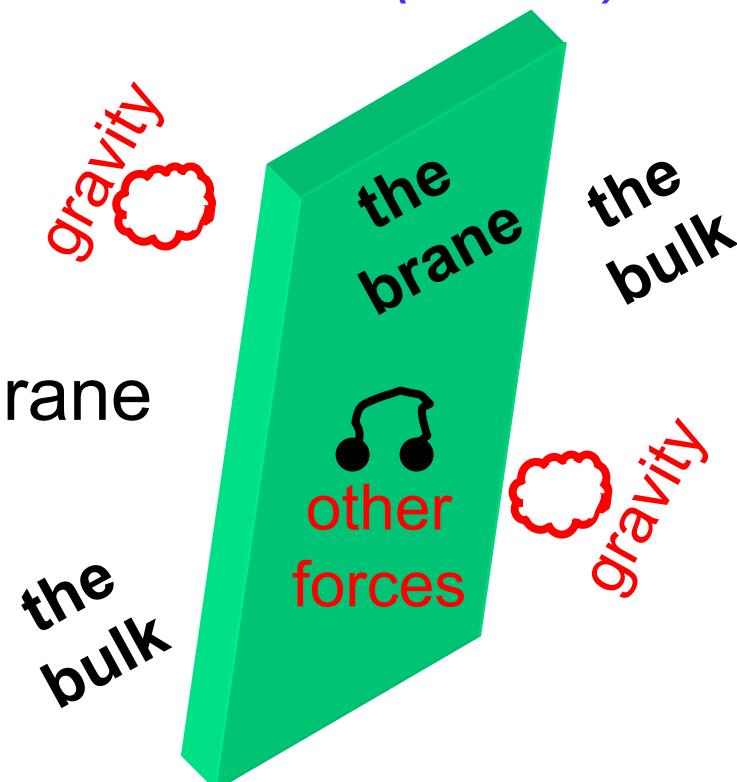
Brane cosmology

- Extra dimensions required in string theory/M-theory
 - $D=26$ for Bosonic string, $D=10$ for Fermionic string
 - What to do with the extra dimensions?
- Matter confined to a $(3+1)$ -dimensional slice (*brane*) in a $(3+1+n)$ -dimensional *bulk*.
 - Gravity lives in the bulk
(closed strings)
 - Other forces confined to the brane
(open strings)



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Brane cosmology

- Starting point: Einstein's equations in 5 dimensions
- Homogeneity/isotropy in 3 spatial dimensions on brane

$$ds^2 = n^2(t, y)dt^2 - a^2(t, y)dx^2 - b^2(t, y)dy^2$$

$$n(t, y=0) = 1 \quad a(t, y=0) = \text{scale factor}$$

- Stress-energy tensor, bulk + brane at $y=0$

bulk:

$$T^A_B = \text{diag}(\rho_{BULK}, -p_{BULK}, -p_{BULK}, -p_{BULK}, -Y_{BULK})$$

brane:

$$T^A_B = \delta(y) \text{diag}(\rho_{BRANE}, -p_{BRANE}, -p_{BRANE}, -p_{BRANE}, 0)$$

Brane cosmology

- Starting point: Einstein's equations in 5 dimensions

$$G^A_B = M_*^{-3} T^A_B$$

$$\frac{3}{n^2} \left[\frac{\dot{a}}{a} \left(\frac{\dot{a}}{a} + \frac{\dot{b}}{b} \right) - \frac{n^2}{b^2} \left(\frac{a''}{a} + \frac{a'}{a} \left(\frac{a'}{a} - \frac{b'}{b} \right) \right) \right] = M_*^{-3} [\rho_{BULK} + \delta(y) \rho_{BRANE}]$$

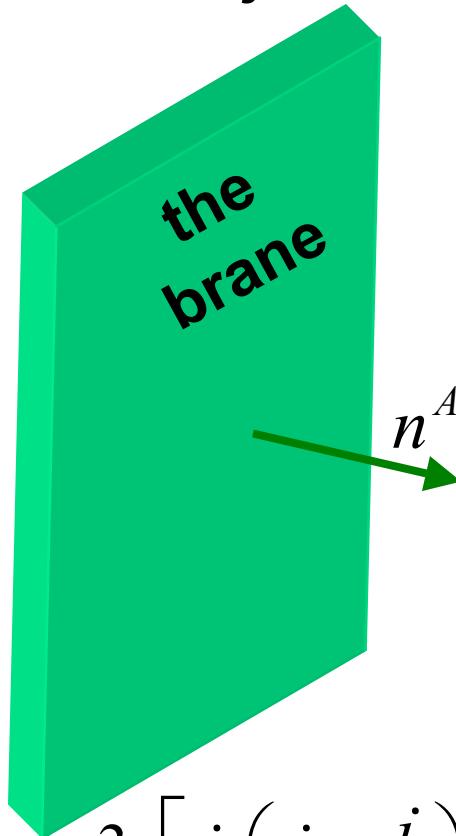
$$\left[\frac{\dot{a}}{a}, \frac{\ddot{a}}{a}, \frac{a'}{a}, \frac{a''}{a}, \frac{\dot{b}}{b}, \frac{\ddot{b}}{b}, \frac{b'}{b}, \frac{\dot{n}}{n}, \frac{n'}{n}, \frac{n''}{n} \right] = -M_*^{-3} [p_{BULK} + \delta(y) p_{BRANE}]$$

$$\frac{3}{n^2} \left[\frac{n'}{n} \frac{\dot{a}}{a} + \frac{a'}{a} \frac{\dot{b}}{b} - \frac{\dot{a}'}{a} \right] = 0$$

$$\frac{3}{b^2} \left[\frac{a'}{a} \left(\frac{a'}{a} + \frac{n'}{n} \right) - \frac{b^2}{n^2} \left(\frac{\dot{a}}{a} \left(\frac{\dot{a}}{a} - \frac{\dot{n}}{n} \right) + \frac{\ddot{a}}{a} \right) \right] = -M_*^{-3} Y_B$$

Brane cosmology

- Israel junction condition (Israel 1966)



- n^A : unit vector normal to the brane
- $h_{AB} = g_{AB} - n_A n_B$: the induced metric
- $\kappa_{AB} = h_A^C \nabla_C n_B$: the extrinsic curvature

$$[\kappa_{\mu\nu}] = -M_*^{-3} T_{\mu\nu}^{BRANE}$$

[....] = discontinuity across the brane

$\langle \dots \rangle$ = continuous part

$$\frac{3}{n^2} \left[\frac{\dot{a}}{a} \left(\frac{\dot{a}}{a} + \frac{\dot{b}}{b} \right) - \frac{n^2}{b^2} \left(\frac{a''}{a} + \frac{a'}{a} \left(\frac{a'}{a} - \frac{b'}{b} \right) \right) \right] = M_*^{-3} [\rho_B + \delta(y)\rho]$$

$$a'' = \langle a'' \rangle + [a'] \delta(y)$$

$$n'' = \langle n'' \rangle + [n'] \delta(y)$$

Brane cosmology

- Starting point: Einstein's equations in 5 dimensions

$$G^A_B = M_*^{-3} T^A_B \quad \text{continuous part + singular part}$$

$\{00\}$ Bulk or Brane Einstein Eq.	$\{0i\}$	$\{0y\}$ Bulk Einstein Eq.
$\{i0\}$	$\{ij\}$ Bulk or Brane Einstein Eq.	$\{iy\}$
$\{y0\}$	$\{yi\}$	$\{yy\}$ Bulk Einstein Eq.

continuous part

Brane cosmology

- Starting point: Einstein's equations in 5 dimensions

$$G^A_B = M_*^{-3} T^A_B \quad \text{continuous part + singular part}$$

singular part

{00} 2 nd Israel condition	{0i}	{0y}
{i0}	{ij} 2 nd Israel condition	{iy}
{y0}	{yi}	{yy}

Brane cosmology

- New Friedmann law Binetruy, Deffayet, Langlois (2000)

$$H^2 = \frac{\dot{a}^2(t, y=0)}{a^2(t, y=0)} = \frac{\Lambda}{6} + \frac{M_*^{-6}}{36} \rho^2 + \frac{c}{a^4(t, y=0)}$$

- Possible solution Randall & Sundrum (2000)

Introduce a tension in the brane $\rho \rightarrow \rho + \sigma$

$$H^2 = \left(\frac{\Lambda}{6} + \frac{M_*^{-6}}{36} \sigma^2 \right) + \frac{M_*^{-6}}{18} \sigma \rho + \frac{M_*^{-6}}{36} \rho^2 + \frac{c}{a^4(t, y=0)}$$

cosmological
constant
(cancels?)

Friedmann
equation

$$\frac{M_*^{-6}}{18} \sigma = \frac{8\pi G}{3}$$

unconventional
corrections

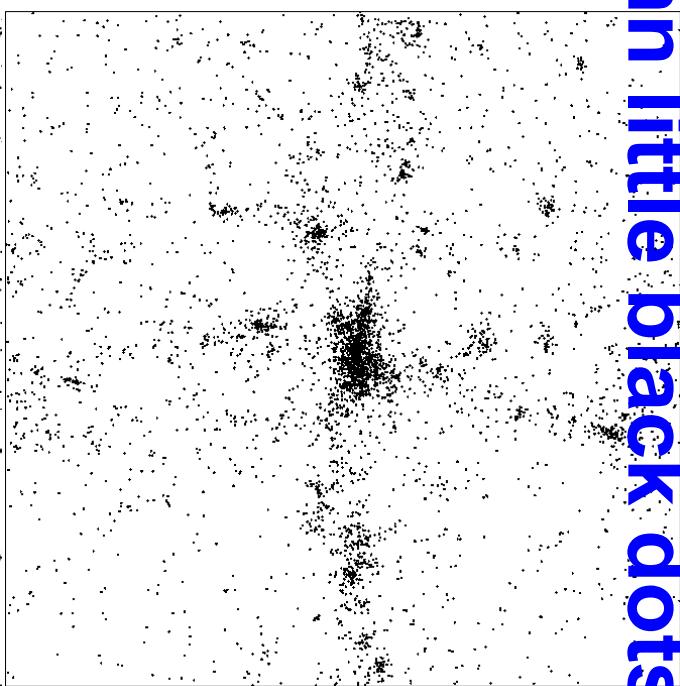
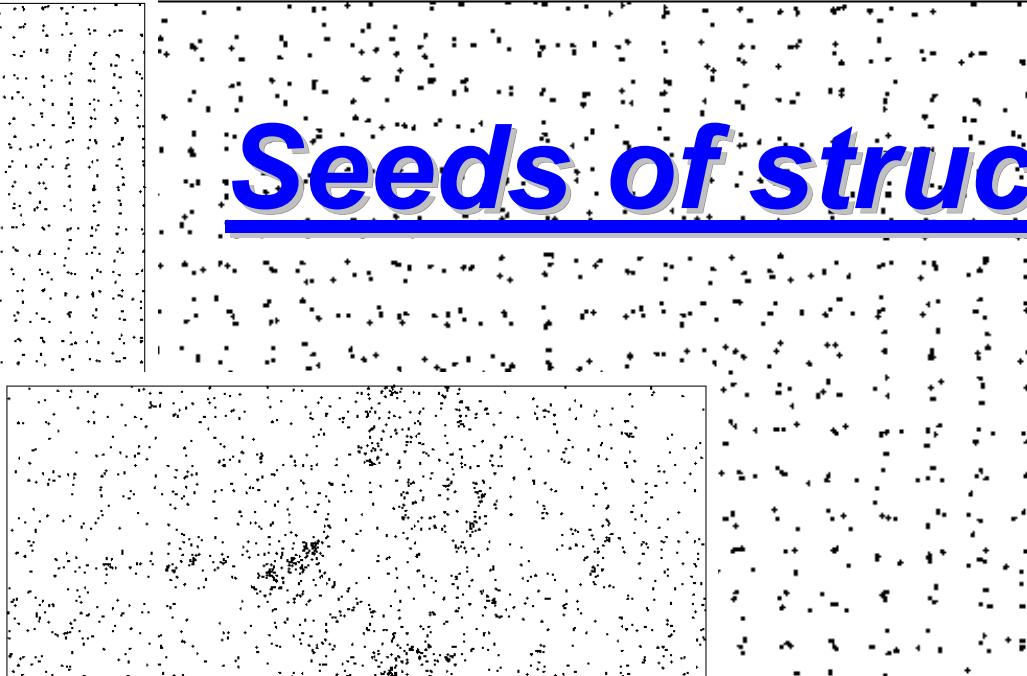
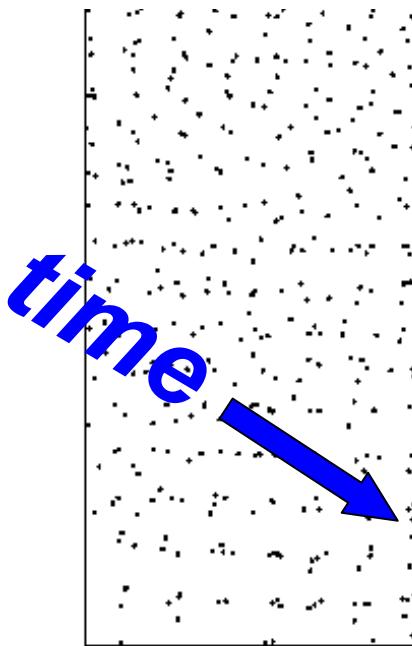
Brane cosmology

Effects on inflation:

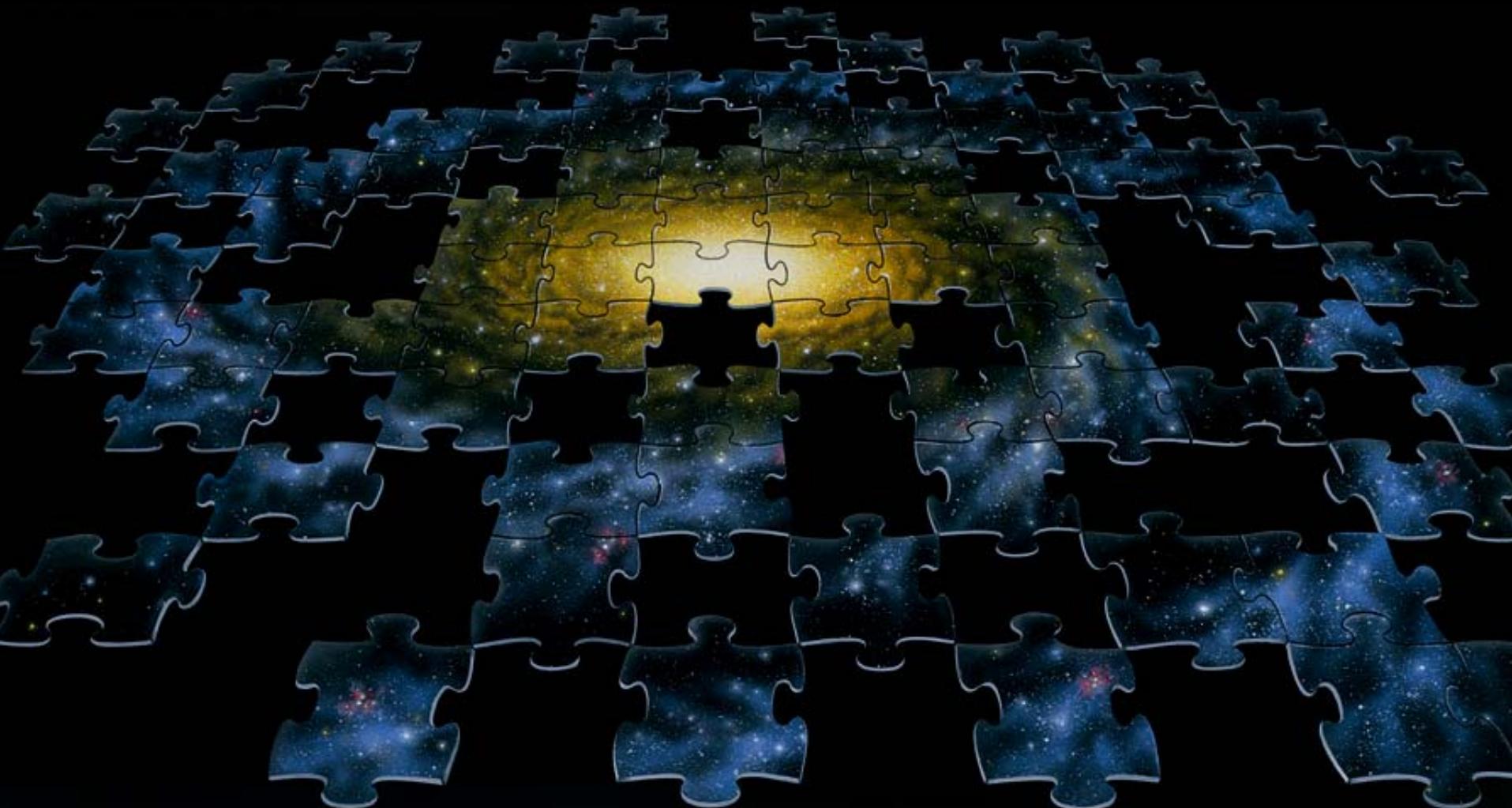
- Modified Friedmann law?
- “Radion” could be the inflaton
- “Transdimensional” corrections?
- Brane collisions (yuckpryotic)?
- Varying G_N (why are extra dimensions stable?)

nature of the damn little black dots

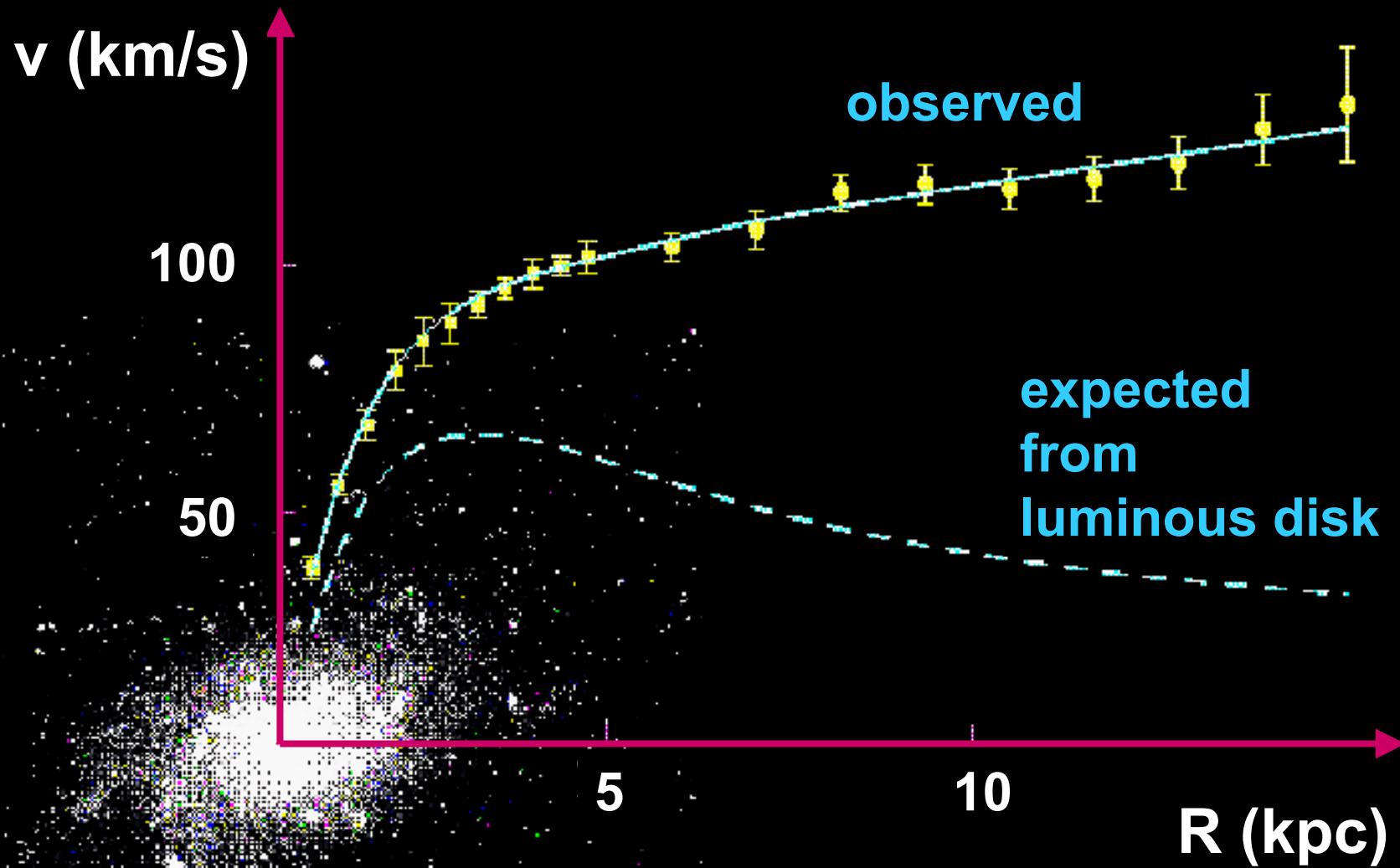
Seeds of structure



Missing Pieces



Dark Matter



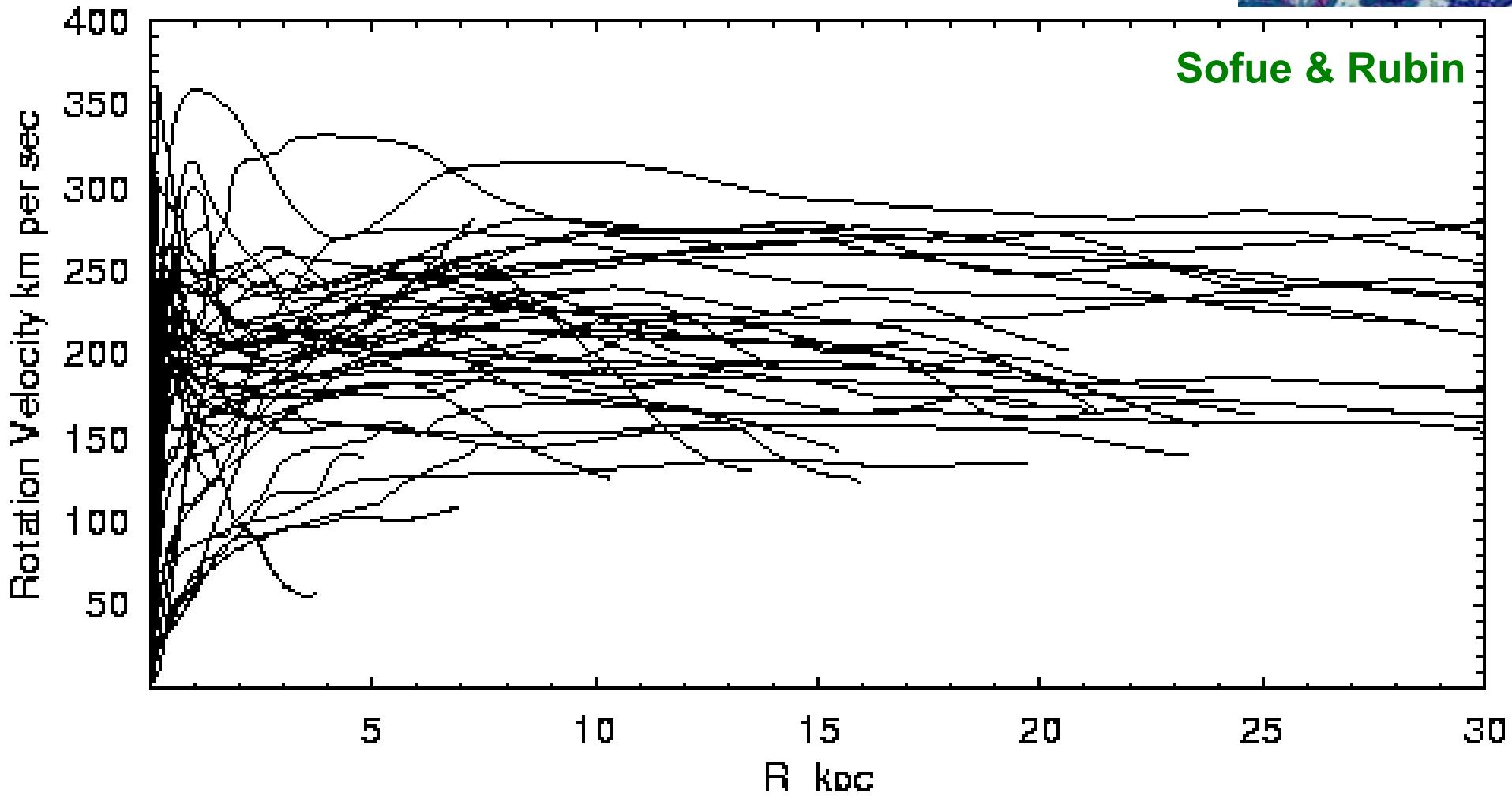
M33 rotation curve

Rotation curves

CO – central regions

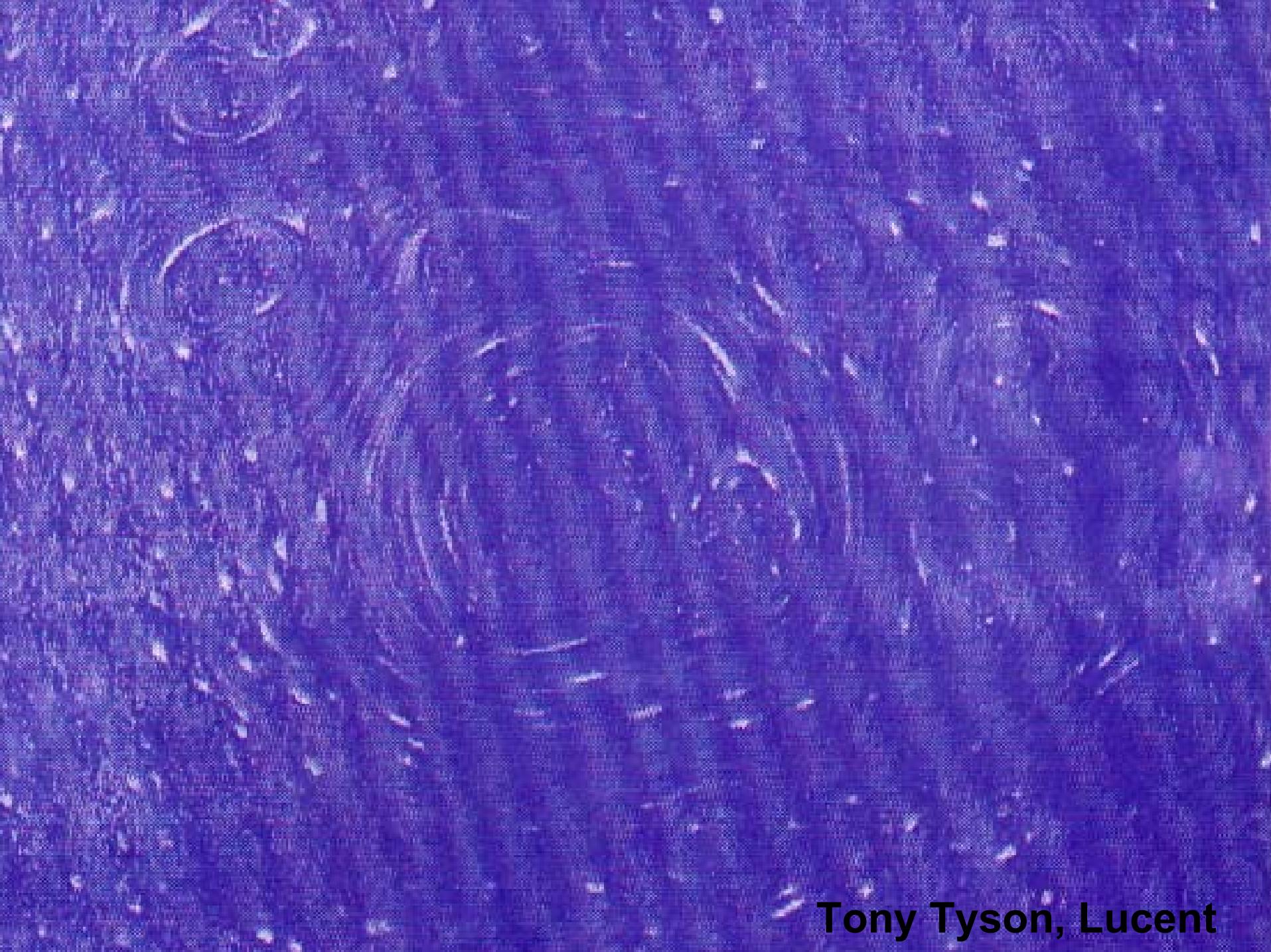
Optical – disks

HI – outer disk & halo





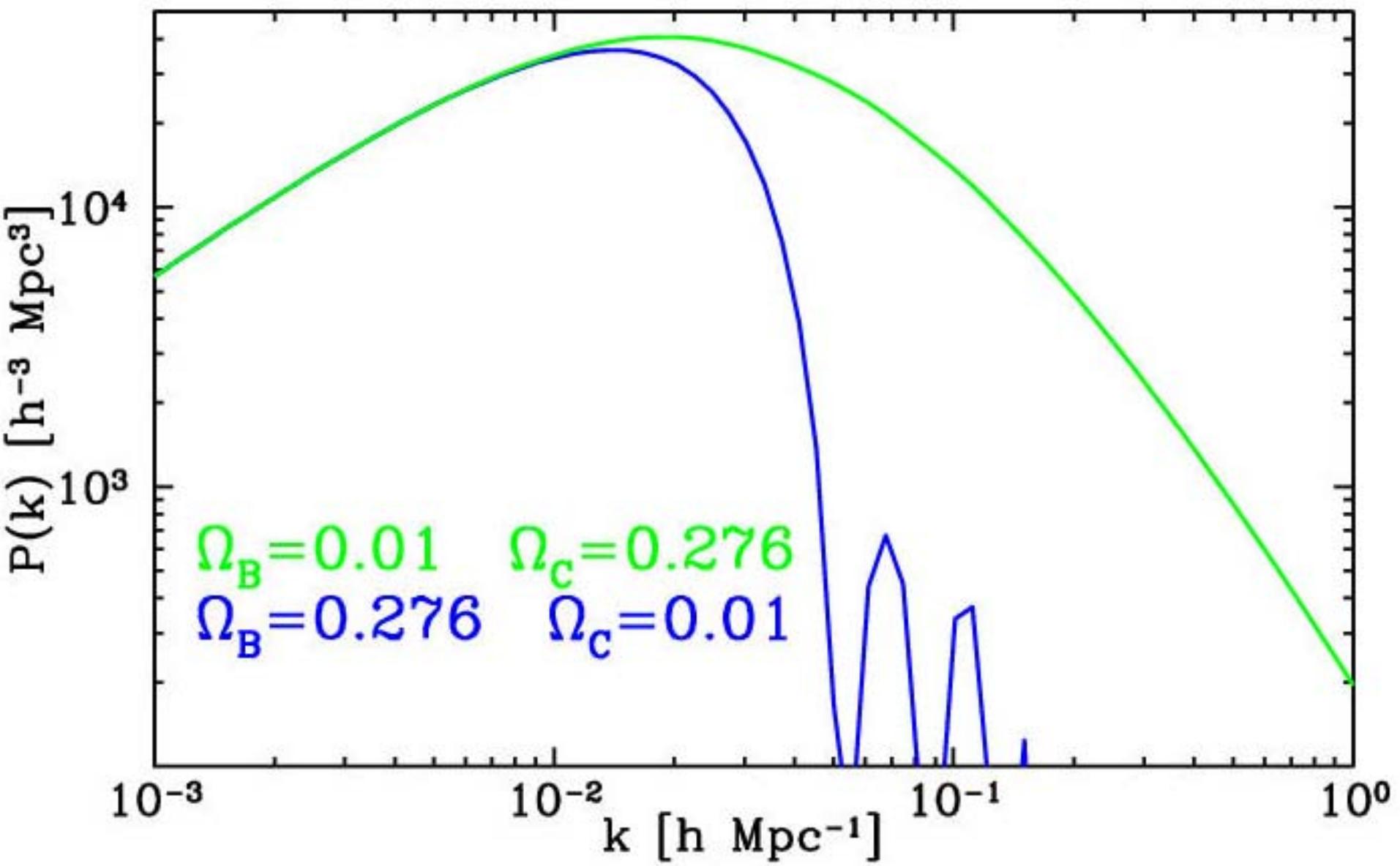
Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope · WFPC2



Tony Tyson, Lucent

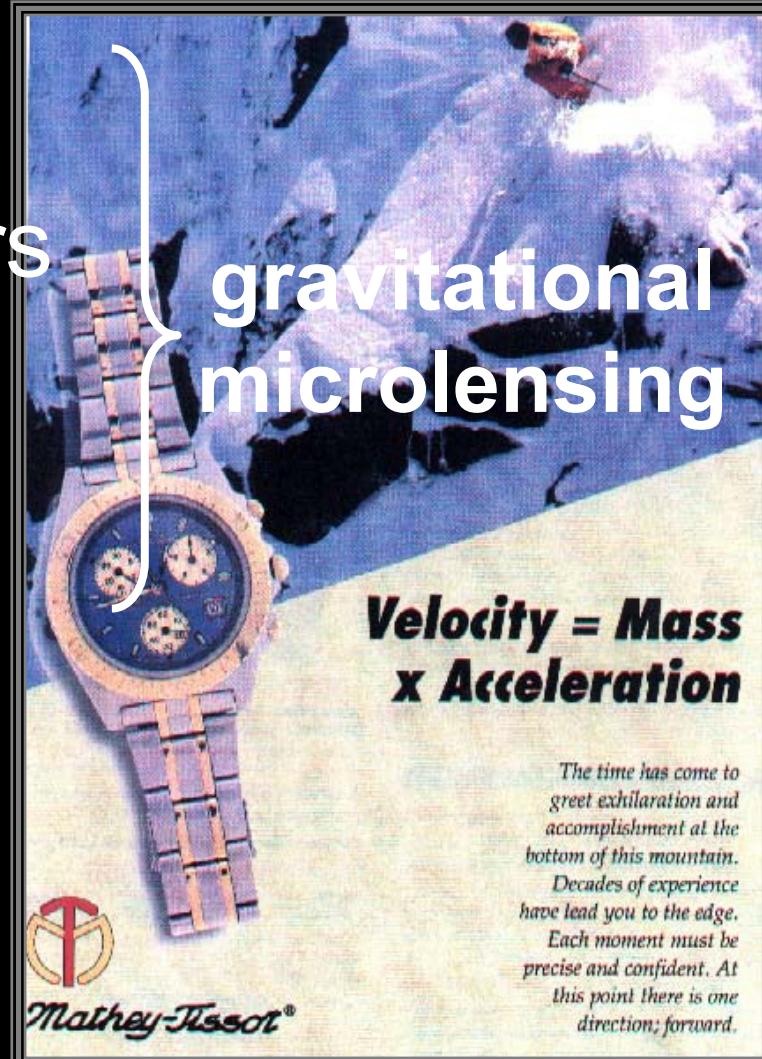


The evolved spectrum



Most of the universe is dark!

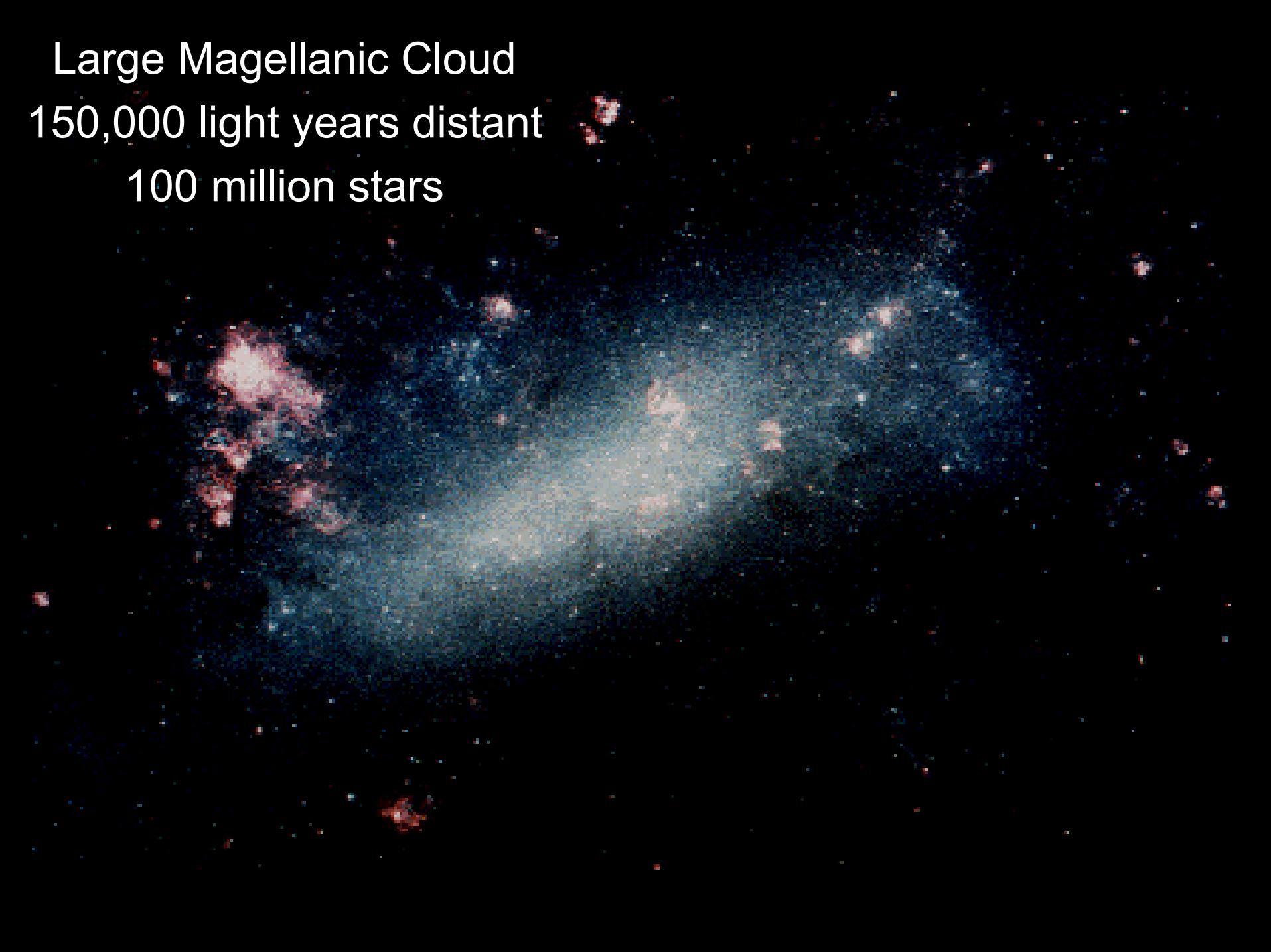
- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars
brown red white
- Black holes

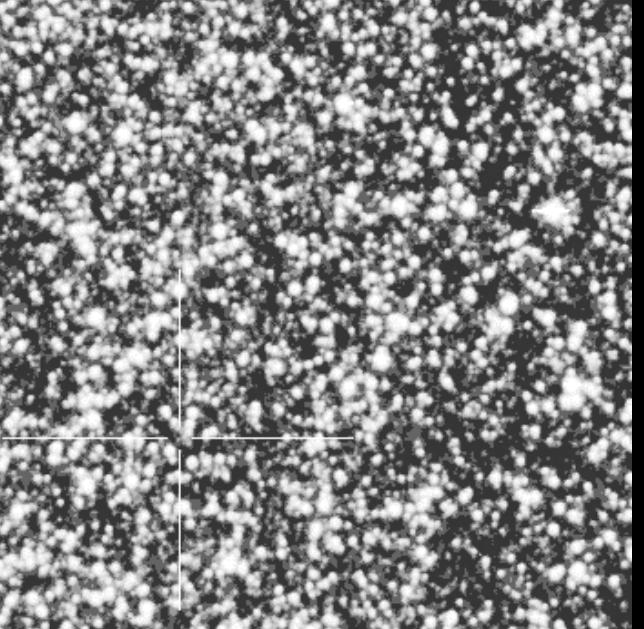


Large Magellanic Cloud

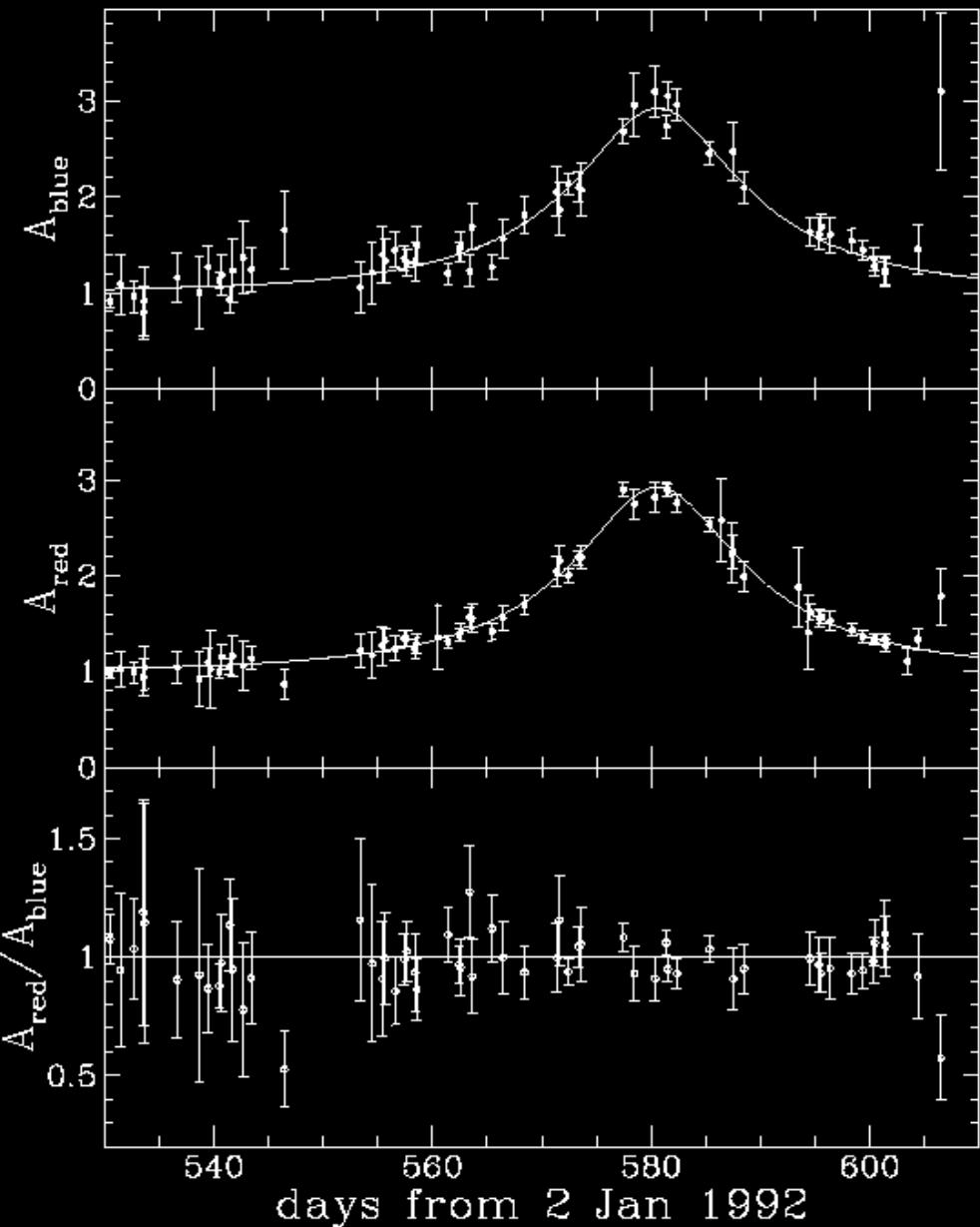
150,000 light years distant

100 million stars

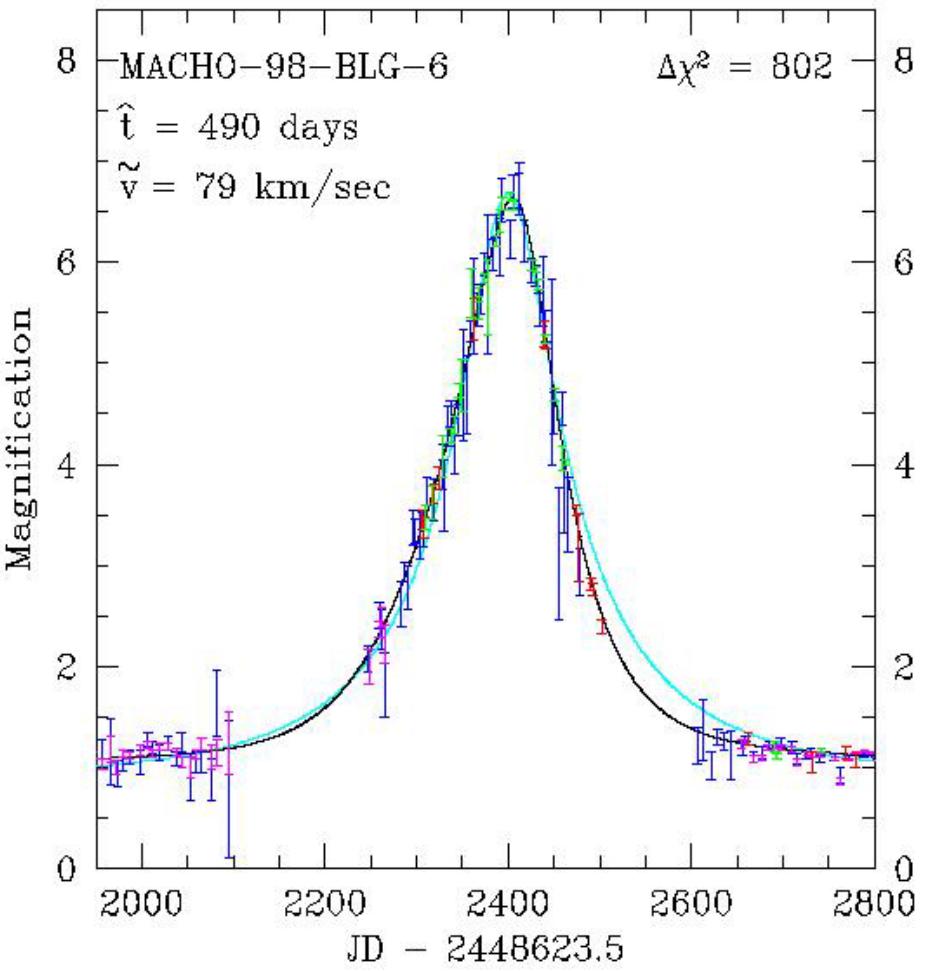




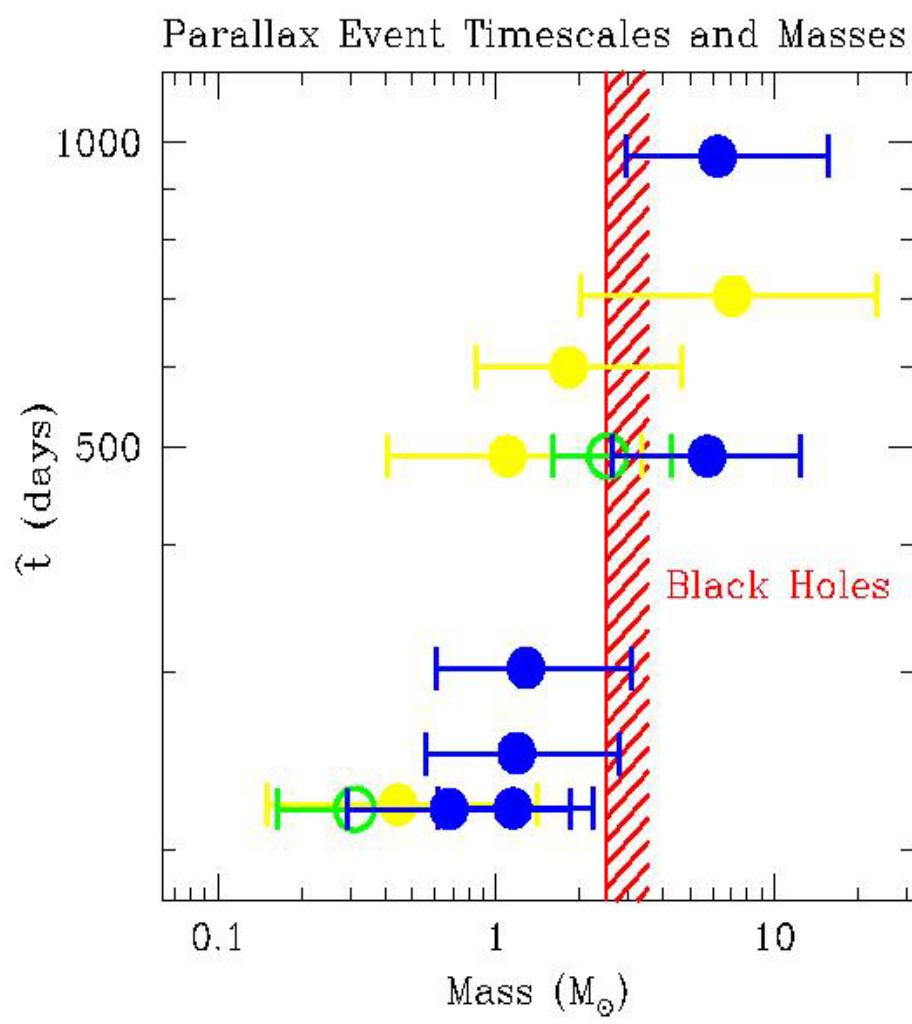
Event 2



Microlensing black-hole candidates



Bennett et al.
(also Mao et al.)



SteHolesagainstBlahholes

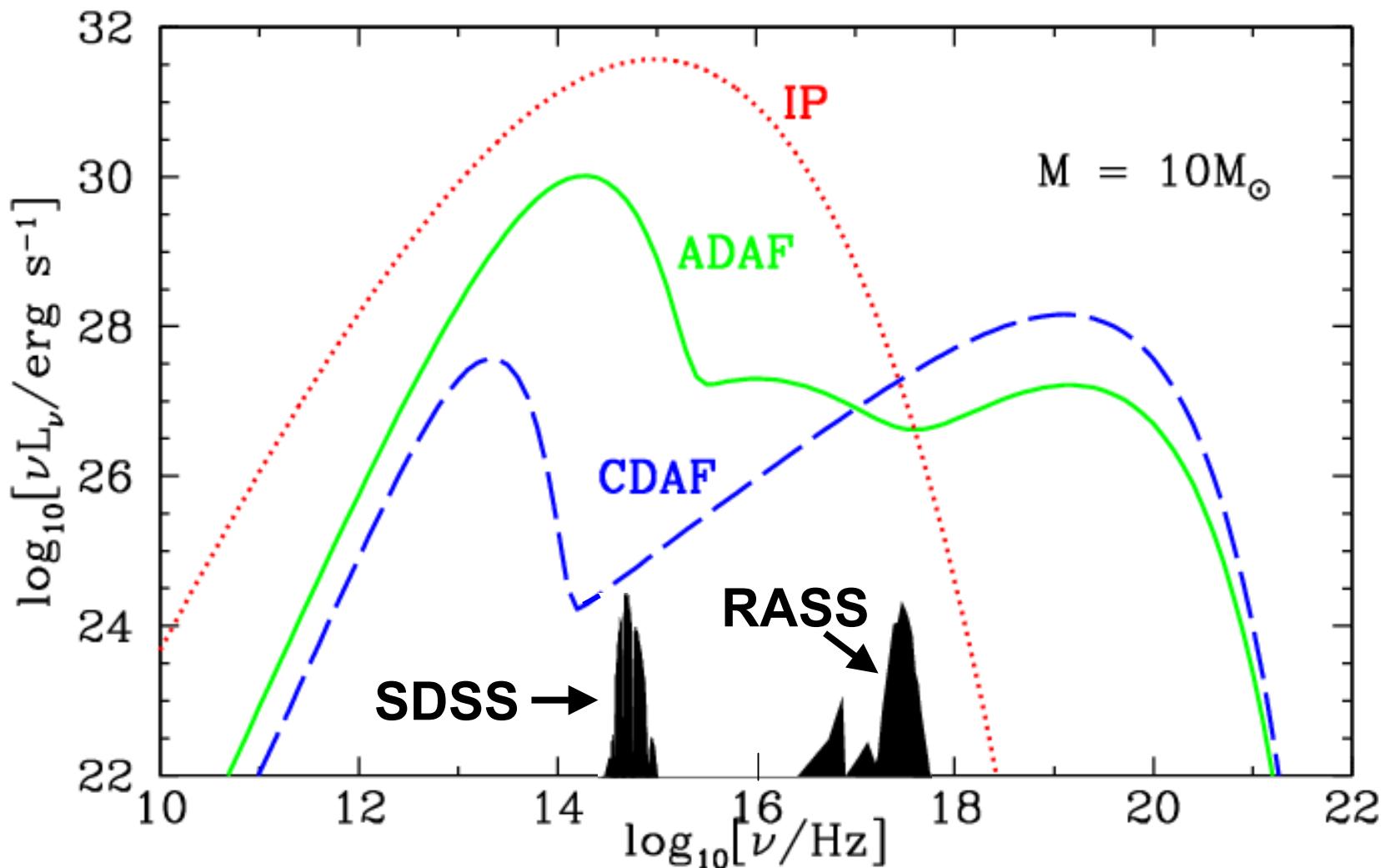
In the Solar Neighborhood

(with Jim Chisholm & Scott Dodelson)

Model spectral energy distributions:

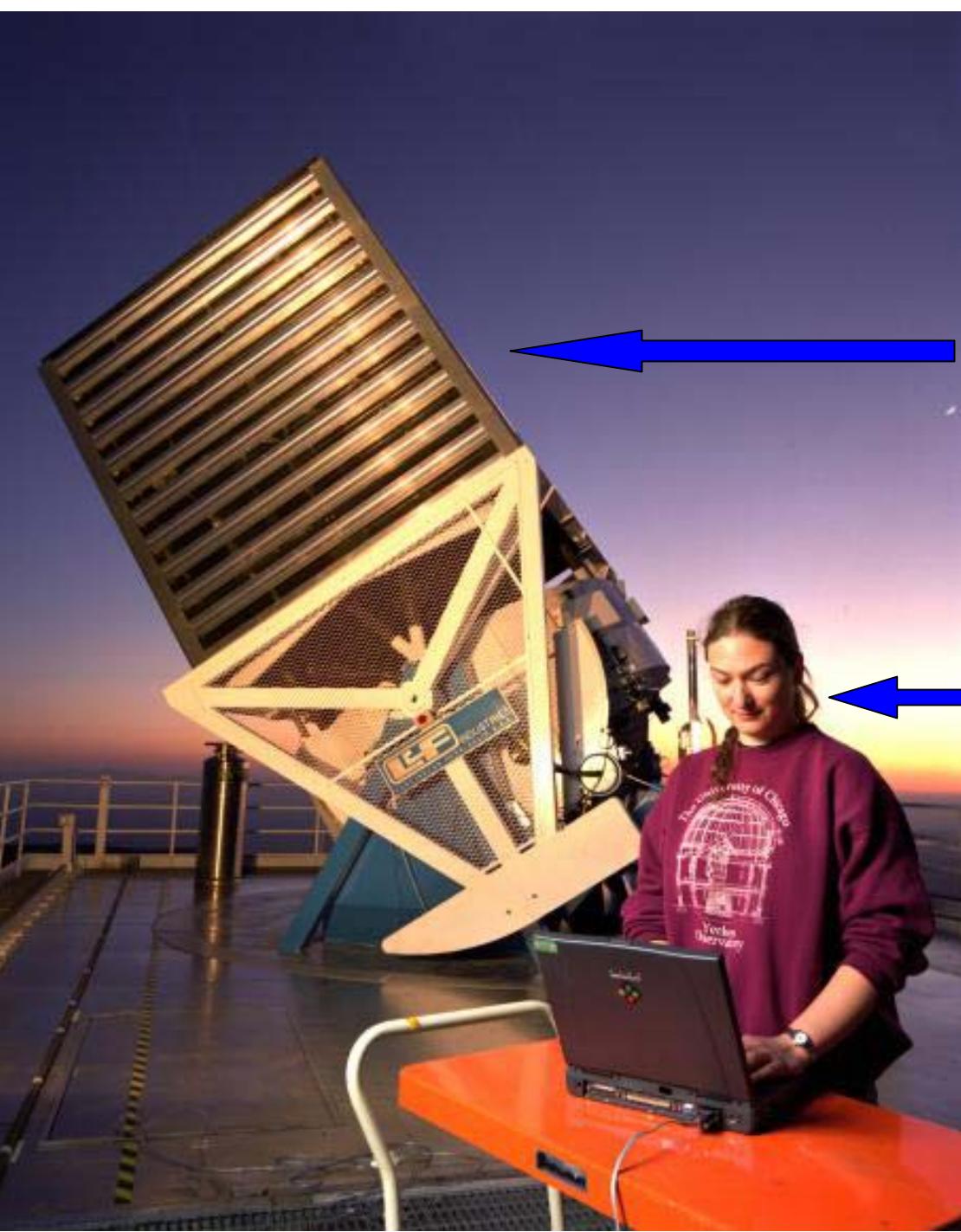
$$L = \int \frac{d\nu}{\nu} \nu L_\nu$$

νL_ν = spectral energy distribution
(contribution per decade)





SDSS



2.5 m telescope

**data acquisition
system**

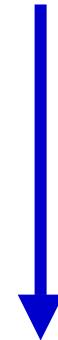
Most of the universe is dark!

- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars
 - brown
 - red
 - white
- Black holes
- The weight of space
- Fossil remnant of the big bang

} gravitational
microlensing

Particle Dark Matter Candidates

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, sneutrino, ...) (cold dark matter)
- axion, axion clusters
- WIMPZILLA
- solitons (B-balls; Q-balls; Odd-balls,....)
 -
 -
 -
 -
 -



Neutrinos?

- Neutrinos are known to exist
three active + sterile?
- Neutrinos are strongly suspected to have mass
- Massive neutrinos contribute to the mass density

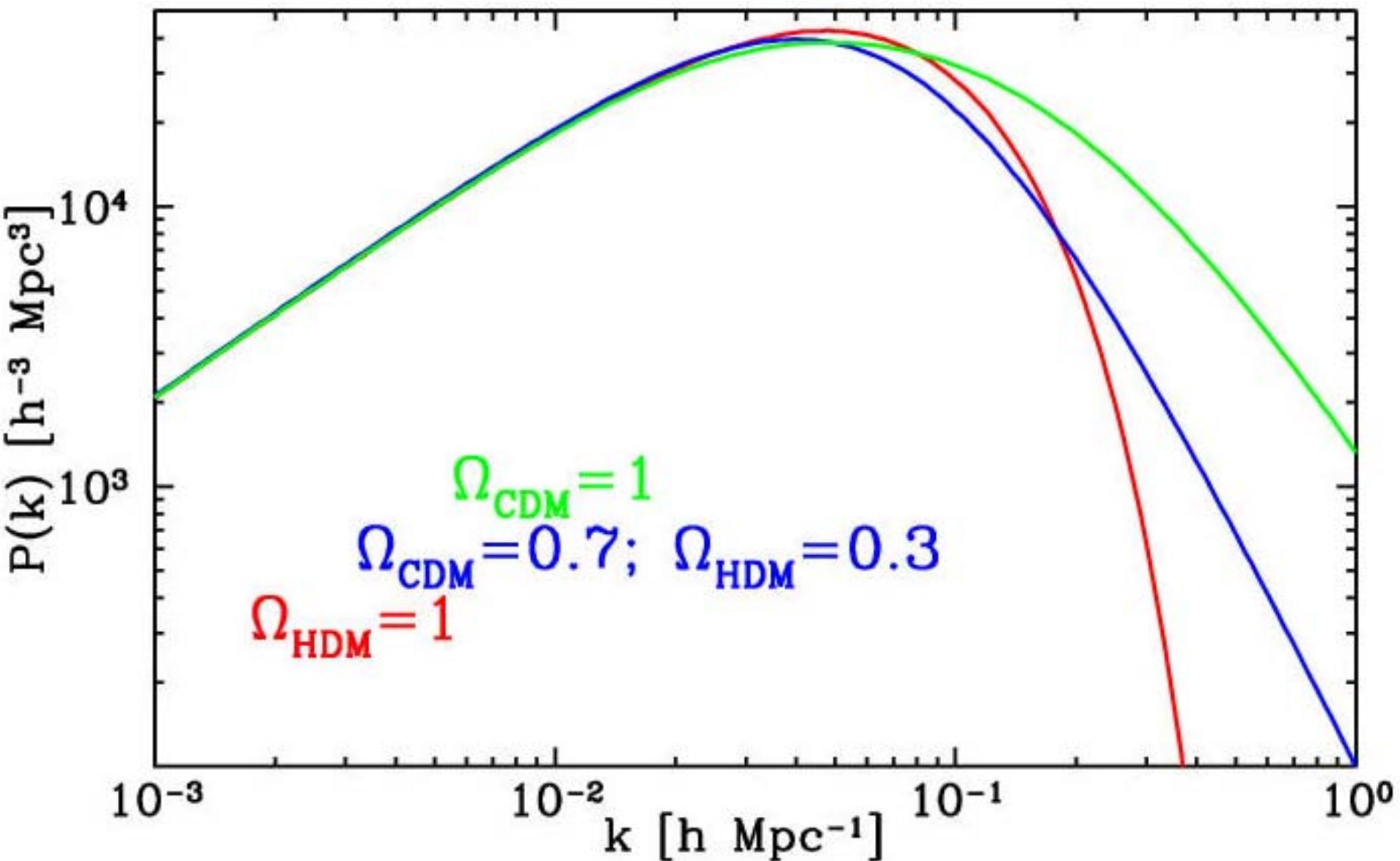
Ballard Firehouse

January 26

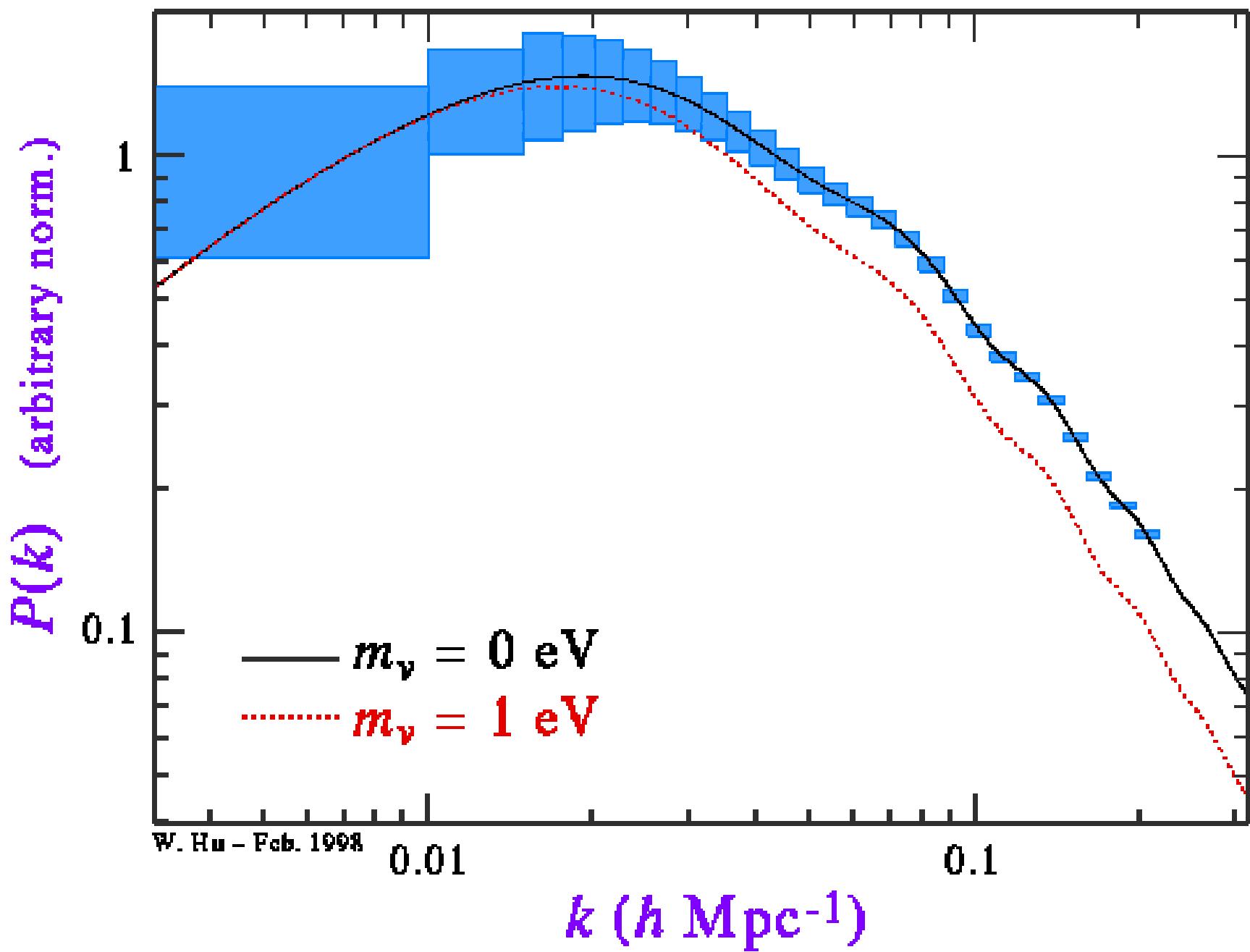
\$3.00

February 9

The evolved spectrum



Projected SDSS BRG



**NEUTRINO MASS AND MIXING
IMPLIED BY UNDERGROUND DEFICIT OF LOW ENERGY MUON-NEUTRINO EVENTS**

John G. LEARNED, Sandip PAKVASA, and Thomas J. WEILER¹

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA

Received 14 March 1988

Recent observations of a deficit of cosmic ray muon-neutrino interactions in underground detectors suggest that the muon neutrinos may have oscillated to another state. We examine possible neutrino mass and mixing patterns, and their implications for vacuum and matter effects on solar neutrinos, on neutrinos passing through the earth, and on terrestrial neutrino beams. By invoking the see-saw mechanism of neutrino mass generation, we draw inferences on closure of the universe with neutrino masses, on the number of generations, on t-quark and fourth generation masses, and on the Peccei-Quinn symmetry breaking scale. Testable predictions are suggested.

(d) Relic tau neutrinos have sufficient energy density to close the university

(6)

flux is de-
to estimate
increased by
only,

(7)

rotating the
basis. Since
ng angle is

(8)

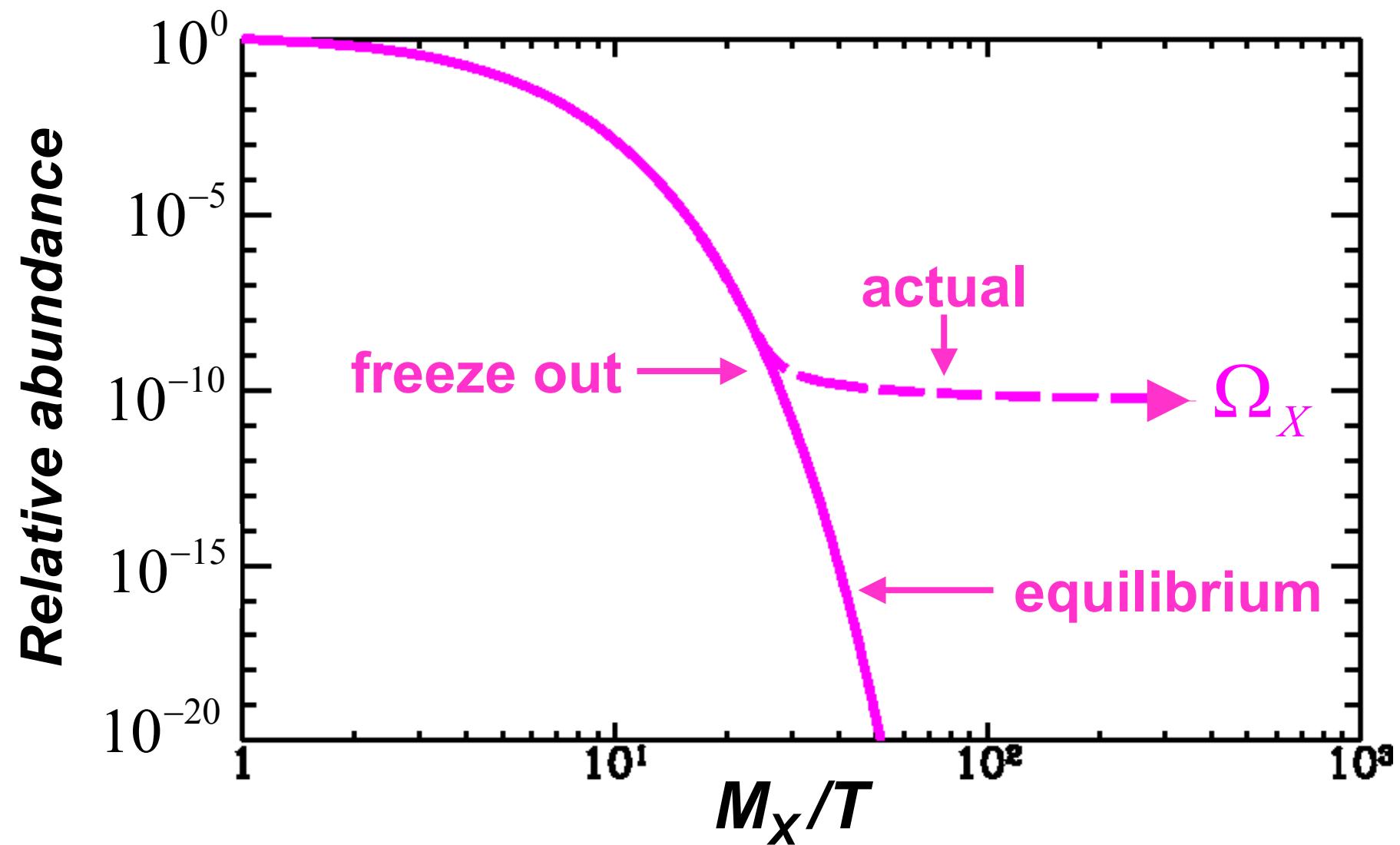
und (from
are forced

and muon-neutrinos (not antimuon-neutrinos) coming through the earth at $E_\nu \sim 50 - 150$ GeV have matter-enhanced oscillations and the muon-neutrinos down/up flux ratio should be even larger than the nonmatter-enhanced expectation (for energies ~ 1 TeV and larger oscillations are suppressed in the earth). Detectors capable of distinguishing μ^- from μ^+ have increased sensitivity to matter effects [10].

(c) A 40% $\nu_\mu \leftrightarrow \nu_e$ conversion should be observable in a detector at a distance L from the neutrino source for the integrated flux satisfying $E/\text{GeV} \lesssim 0.04 L/\text{km}$.

(d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot dark matter over cold): the tau-neutrino mass may be determined from the time spread of events from a galactic supernova. (e) There are only three generations: the mass of a fourth-generation heavy lepton is bounded from below by the UA1 data [12] and from

Cold thermal relics



$$\Omega_X \propto \sigma_A^{-1} \quad (\text{independent of mass})$$

Desperately seeking SUSY

Hierarchy problem:

- fundamental scale is Planck mass*
- particles have mass much less than Planck mass
 - gauge bosons protected by gauge symmetry
 - fermions protected by chiral symmetry
 - scalars (e.g., Higgs) defenseless!
- introduce supersymmetry to protect scalars

Supersymmetric Standard Model:

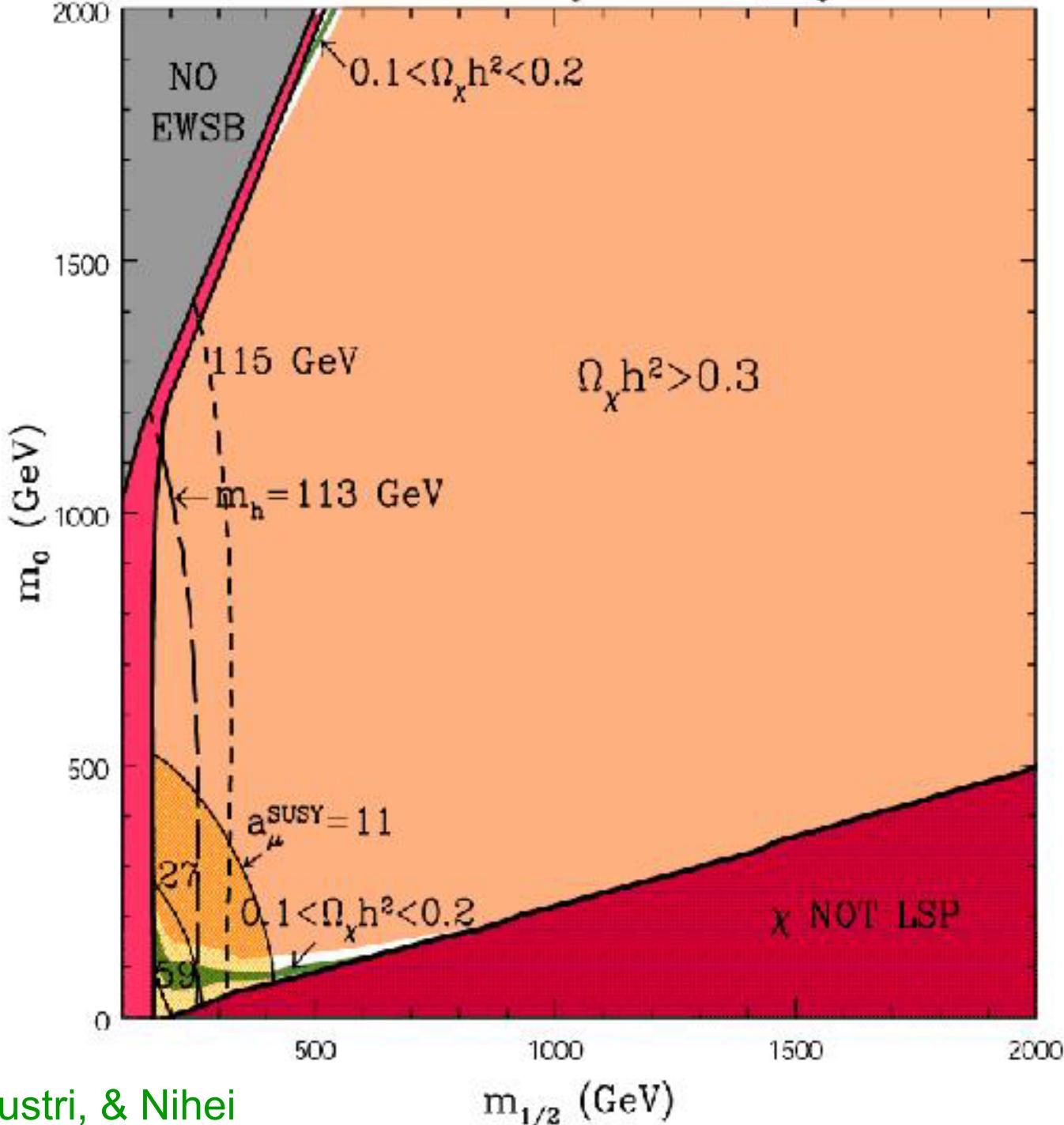
105 parameters

Constrained Minimal Supersymmetric Standard Model:

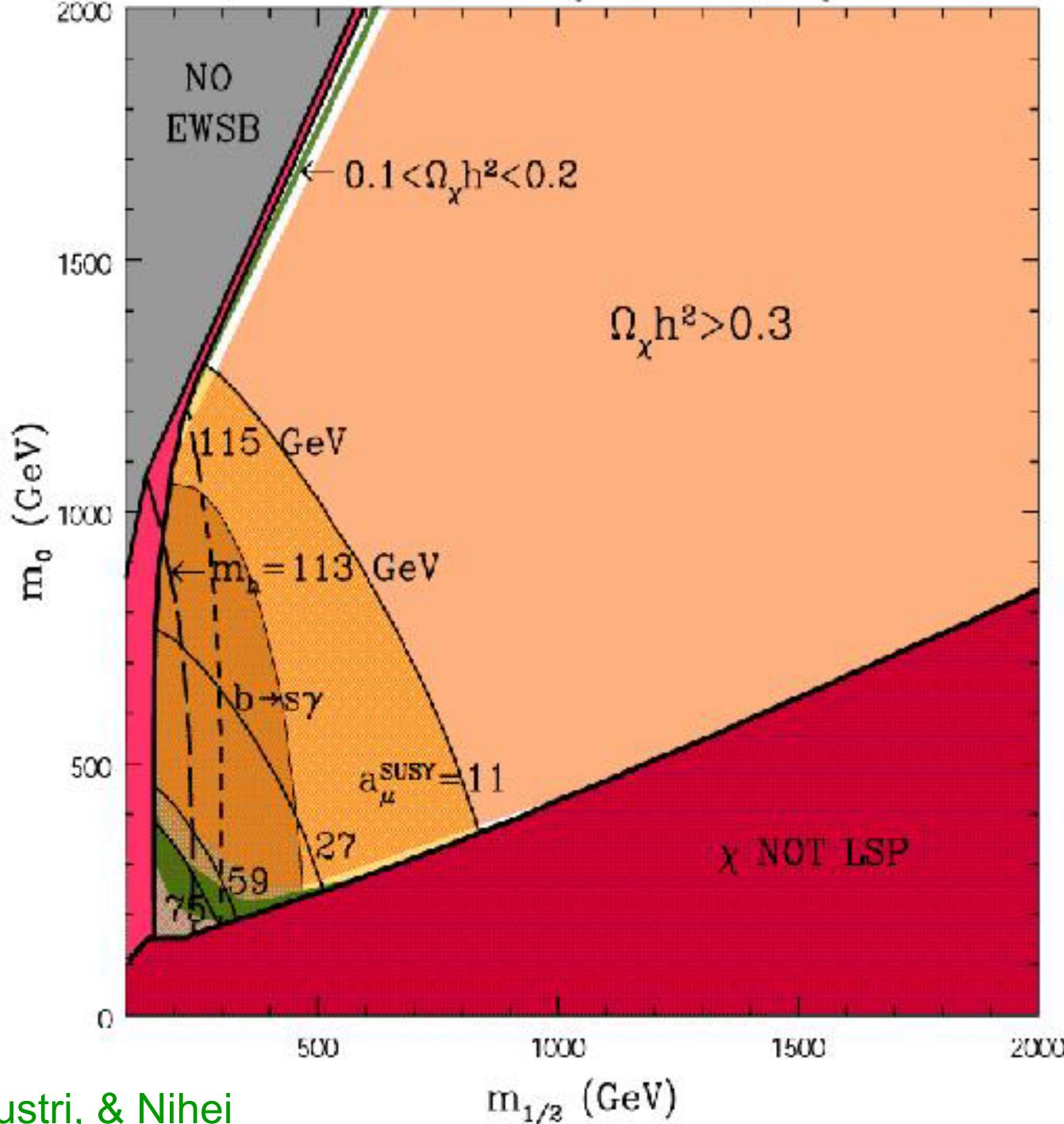
4 parameters: A_0 , $\tan \beta$, $m_{1/2}$, m_0 , $\text{sign}(\mu)$

* Assumed here to be $G_N^{-1/2}$

$\tan \beta = 10$

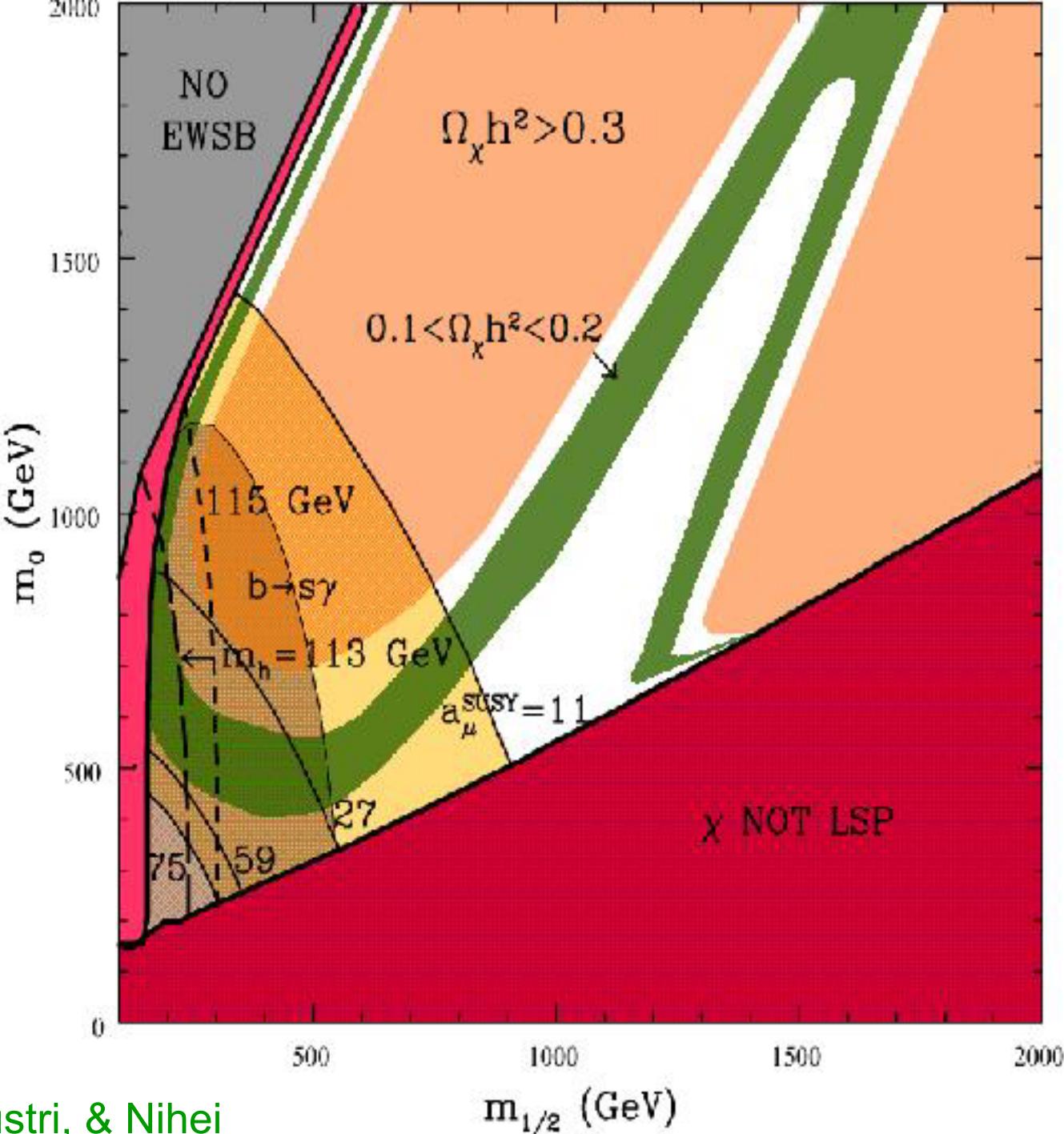


$\tan \beta = 40$



$\tan \beta = 50$

wide resonance in
neutralino annihilation

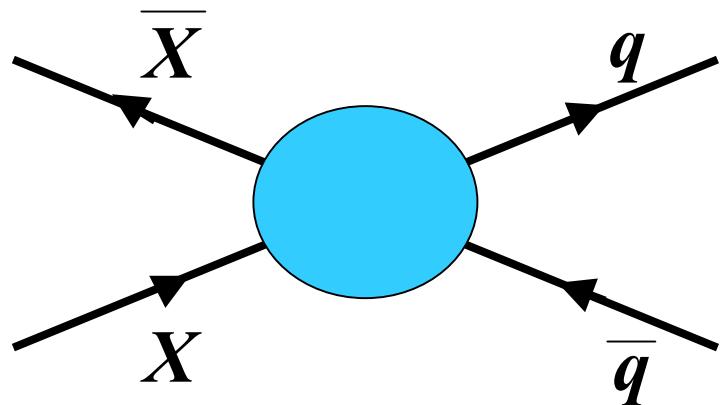


Cold thermal relics

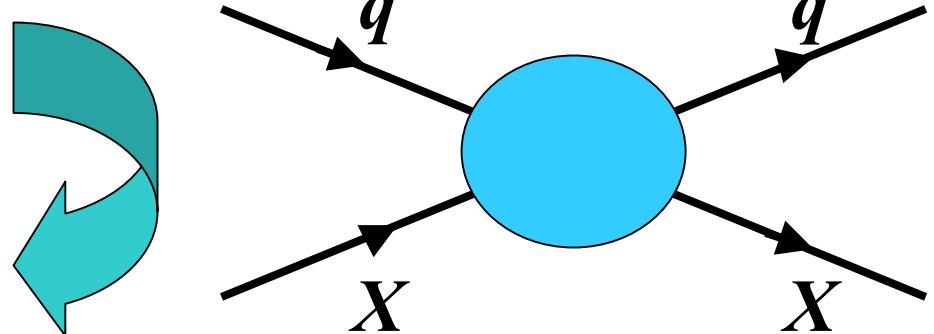
$$\Omega_X h^2 \sim \langle \sigma_A v \rangle^{-1}$$

$$\Omega_X \rightarrow \sigma_A$$

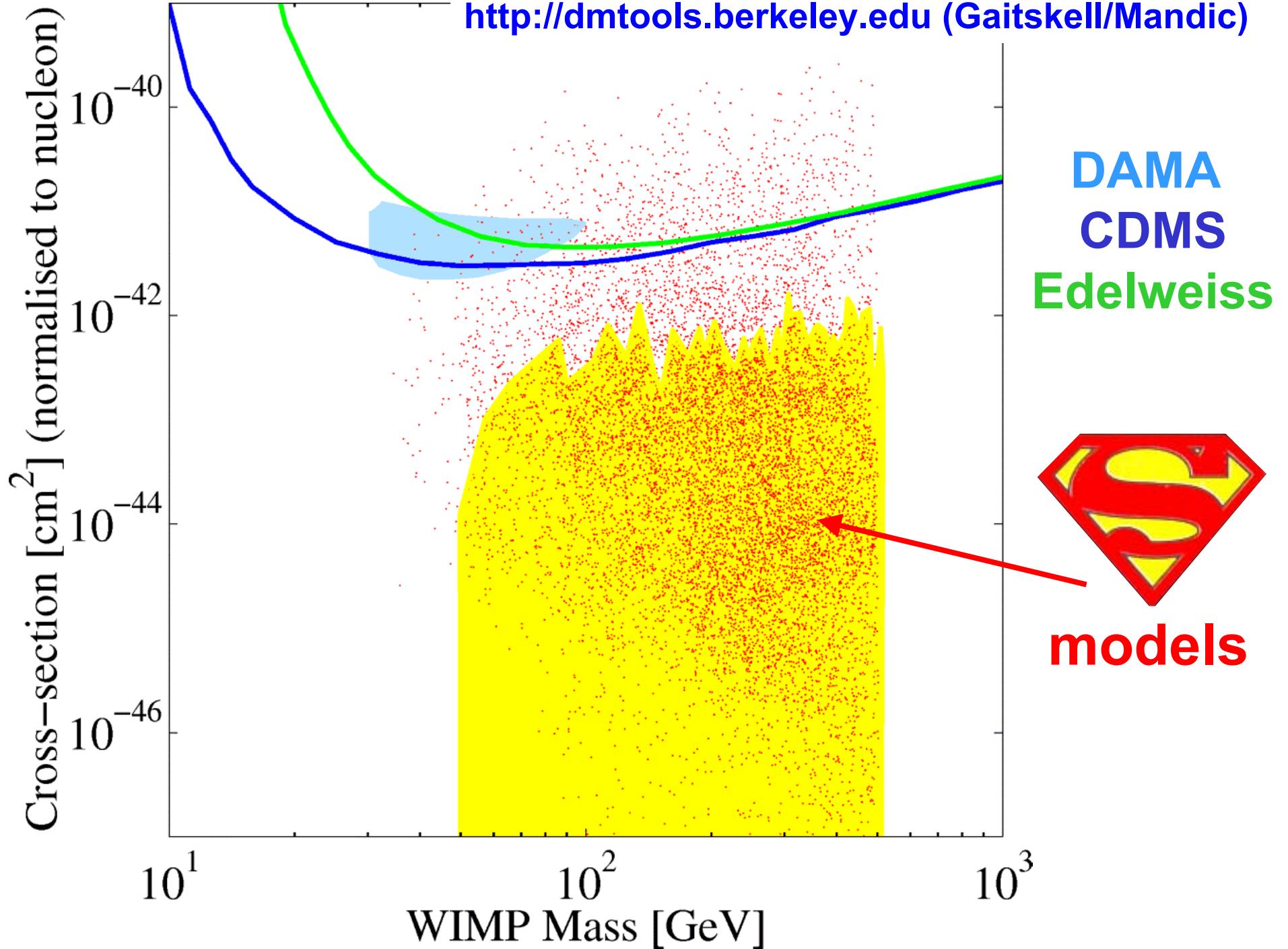
$$\sigma_A \rightarrow \sigma_S$$



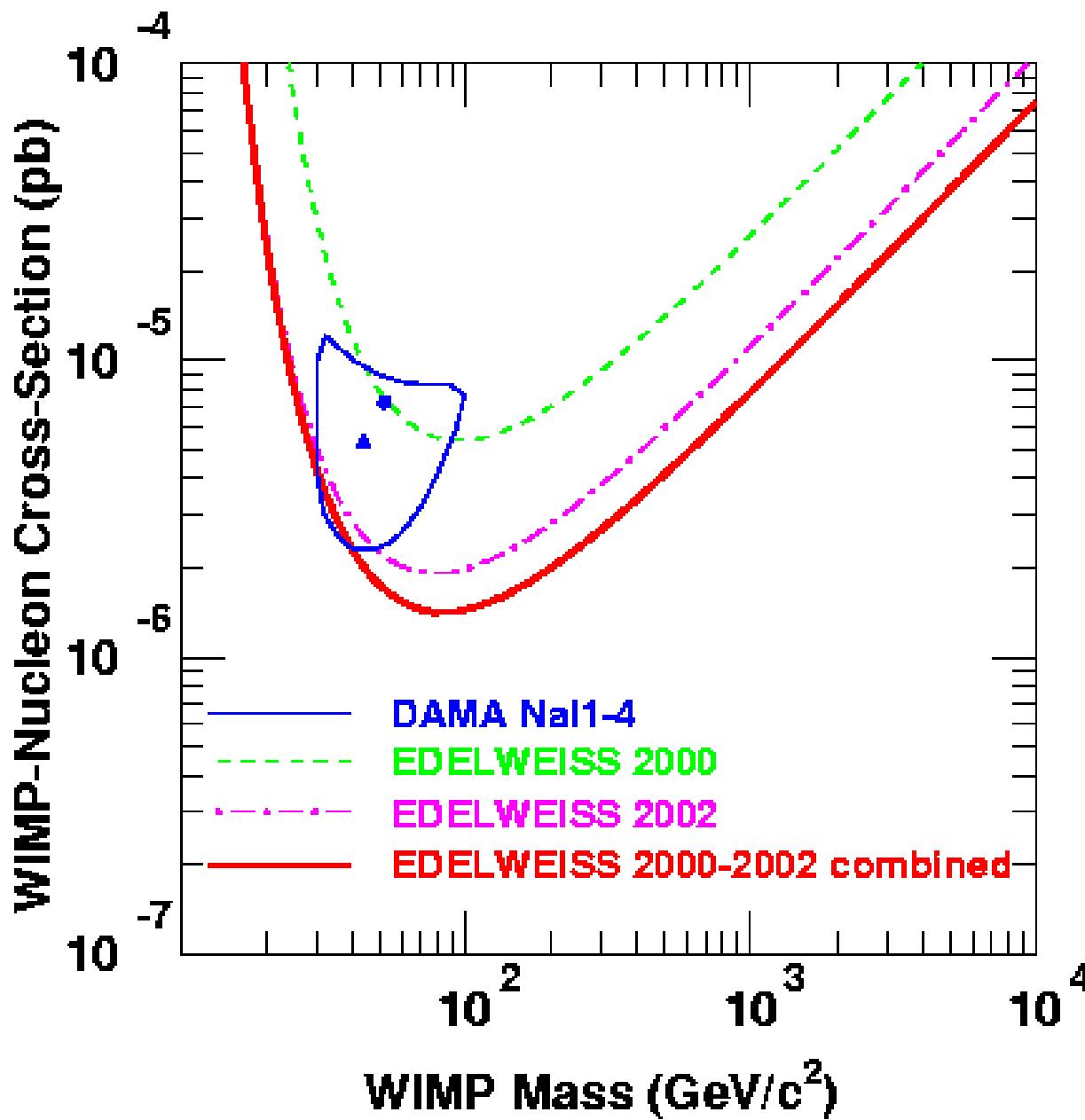
$$X \bar{X} \leftrightarrow q \bar{q}$$



$$X q \leftrightarrow X q$$



Cold thermal relics



CMSSM neutralino dark matter

- SUSY not constrained, minimal, or standard
- large $\tan \beta$
 - infrared quasi-fixed point of top Yukawa coupling
 - large m_0 - focus-point region
- small $\tan \beta$
 - fine tuning for coannihilation

Thermal WIMP: interaction & mass limit

Ω_X depends on the annihilation strength ($\Omega_X \propto \sigma_A^{-1}$)

$\Omega_X \approx 1$ annihilation strength \approx electroweak scale

annihilation strength \rightarrow interaction strength

$\sigma_A \leq \frac{8\pi}{m_X^2}$ unitarity limit to the cross section

$$\Omega_X \leq 1 \Rightarrow M_X \leq 200 \text{ TeV}$$

**Thermal WIMP: Interaction strength determined
Mass undetermined (but < 200 TeV)**

Nonbaryonic dark matter

Familiar candidate: thermal relic, i.e., a neutralino

“a simple, elegant, compelling explanation for a complex physical phenomenon”

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- *Tommy Gold*

Dark matter may be produced in inflation (the alarming phenomenon), be superheavy, and be sterile (or it may interact).

Dark Matter

WIMP

or

WIMPZILLA



Cosmology and the origin of structure

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Rocky V: Dark matter

Xth Brazilian School of Cosmology and Gravitation

August 2002, Mangaratiba

Rocky Kolb

Fermilab, University of Chicago, & CERN